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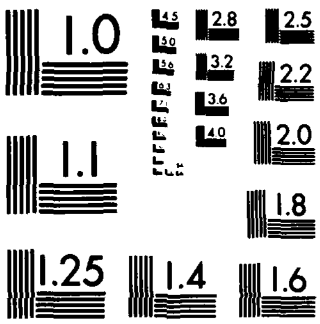

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS 02139

Research on High-Strength Steels with an
Improved Resistance Against Weld Cracking

by

Frederick Frank Hillenbrand, III

OE
SM (NA & ME)

Course XIII A
June 1984

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RESEARCH ON HIGH-STRENGTH STEELS WITH AN IMPROVED RESISTANCE AGAINST WELD CRACKING

by

FREDERICK FRANK HILLENBRAND, III

B.E., State University of New York, Maritime College
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RESEARCH ON HIGH-STRENGTH STEELS WITH AN

IMPROVED RESISTANCE AGAINST WELD CRACKING

by

FREDERICK FRANK HILLENBRAND, III

Submitted to the Department of Ocean Engineering on May 11, 1984 in partial fulfillment of the requirements for the Degrees of Ocean Engineer and Master of Science in Naval Architecture and Marine Engineering

ABSTRACT

Current American practices are surveyed to determine which weld cracking tests are used, and what methods are used to prevent and control weld cracking. The cracking resistance of a newly developed quenched and tempered High Strength Low Alloy (HSLA) steel, K-TEN80CF, with an advertised minimum yield strength level of 70 kgf/mm² (100 KSI) is researched. Using the Tekken self-restraint weld cracking test and Gas Metal Arc (GMA) welding, the new steel is compared against two commonly used high strength steels, T-1 and HY-80, at various preheat levels. An investigation is made into the possible impacts of the cracking test results, based partially upon the survey of practices.

The steel test plates were subjected to X-ray, dye penetrant, and macroscopic and microscopic examinations to determine the extent of any existent cracking. It was found that the HSLA steel exhibited an excellent resistance to cracking, even when welded without the use of preheat; whereas, the T-1 and HY-80 steels had to be preheated in order to ensure cracking did not occur.

In addition to being less expensive than either T-1 or HY-80, the ability of HSLA steels to be welded using a minimal amount of preheat will save on both erection time, and the costs associated with weld site preparation.

Thesis Supervisor: Dr. Koichi Masubuchi

Title: Professor of Ocean Engineering and Materials Science.

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Professor Masubuchi has been instrumental to my education at MIT. Because of his instruction and assistance I have obtained knowledge in the areas of welding engineering and state of the art steel processing. This information will be extremely useful in my future engineering career as a United States Naval officer. The sponsorship of my studies by the Navy has made it possible for me to conduct my postgraduate studies at MIT, a feat which I could not otherwise afford.

Mr. Anthony Zona was invaluable both as a friend, and as a consultant. His knowledge of welding procedures, how to practically get things done, and MIT in general were irreplaceable. Dr. George Clems of the Republic Steel Corporation has been extremely helpful, aiding in the survey of United States industry, and suggesting other valuable points of contact. Mr. Mario Aloisi and Mr. Umberto Fazio of the LNS shop dedicated a significant portion of their time to the manufacturing of the steel test plates. I am sure they are extremely glad to see that this project actually has ended. Always ready to assist, Ms. Muriel Bernier deserves an award for efficient secretarial and administrative skills. Furthermore, her drafting work and lettering of the figures included in this thesis are works of art. Mrs. Eileen MacIntosh has helped build my ego significantly as she proof read this work. She not only corrected my errors, but she also helped me to maintain a consistent level of quality. Graduate students, and fellow researchers Andrew DeBicarri and Michael Purcell were always available during the testing, and without their help this project would never have been completed.

My wife Libby has had to give up the most in order for this thesis to become a reality. Her love, support and tolerance of my long days and odd working hours made my task that much easier. Without her I would not have been able to devote as much time to this thesis; therefore, she deserves considerable credit for the final product. I love her dearly.

TABLE OF CONTENTS

List of Figures

List of Tables

I. Introduction

Global usage of high strength steels increases each year. This is due to both the expanding demands of the presently existing markets and the development of new applications. High strength steels are typically used in the fabrication of military vessels, ice-breakers, nuclear power components, oil exploration and recovery equipment, railroad cars and heavy construction equipment. The selection of a high strength steel by the designer is generally predicated by the anticipation of an extremely harsh environment. Future applicatior of high strength steels will also be subjected to seve loadings. Continued development of the arctic by the oi. companies offers opportunities for immediate expansion of the present high strength steel market. Soon additional markets may appear in the rapidly expanding development of space.

One of the main detrimental characteristics of high strength steels is their sensitivity to delayed cracking. Many researchers have spent years studying the problems and causes of delayed cracking. Although the mechanisms of delayed cracking are fairly well understood today, the precautions which are used to prevent it impose many rigid guidelines. These guidelines require that strict procedures be followed at all points in the erection of a structure fabricated with high strength steels.

It is believed by the steel manufacturers that the generic family of steels labeled "High Strength Low Alloy"

(HSLA) steels will overcome many of the drawbacks that accompany the currently used high strength steels. One adverse property that has received considerable attention is the high level of difficulty associated with the fabrication of a structure using high strength steels. In an effort to develop a better product, more attractive to the steel consumers, steel manufacturers have devoted many millions of dollars researching and perfecting the science of manufacturing HSLA steels. As evidenced by the recent surge in interest by major steel consumers, there is reason to believe that the efforts of the steel producers will be well rewarded.

The first true HSLA steel was developed in 1929 as a refinement of a steel that exhibited the property of good atmospheric corrosion resistance. This steel was initially marketed in 1933 under the trade name COR-TEN by United States Steel.

In the half century since its introduction, HSLA steels have been manufactured in many different ways. Chemical compositions were frequently varied when corrosion resistant properties were not as rigid, or in an attempt to further increase the yield point of the steel. Shortly after the introduction of COR-TEN the addition of microalloys was refined to the point of usefulness.

Microalloying high strength low alloy steels has evolved from the exclusive usage of vanadium, through the discovery of niobium's additional strengthening values, to the point where today even nitrogen is occasionally added.

The numerous catastrophic failures of large welded structures, most notably the numerous *Liberty* class ships in World War II, led to research in the areas of fracture toughness and the ductile-to-brittle transition temperature. Research concentrating on the microstructure of steel has led to many discoveries and improvements in HSLA steels, resulting in the versatile product now available.

Defining a high strength low alloy steel is not easy. In fact, the term has been applied very loosely to at least six different "types" of steels [46]. These include:

Weathering steels

Control Rolled steels

Microalloyed steels

Dual Phase steels

Pearlite Reduced steels

Acicular Ferrite steels

The purpose of this study is threefold. The objectives of the first task include: determining which kinds of high strength steels are in use in the United States, along with their strength levels and thicknesses; surveying the American industry to determine which cracking tests are commonly performed in the United States; and to discover what methods are used to both prevent and control weld cracking.

The second task will compare a high strength low alloy steel against two other commonly used high strength steels for resistance to delayed cracking. It is the intent of this task to determine a range of restraint, below which cracking will not occur in the tested HSLA steel, but will occur in the other tested high strength steels.

Finally, task three will attempt to evaluate the possible impacts that the new HSLA steels will have upon both the current steel market and the fabricators who use these types of steels.

II. BACKGROUND

The first use of metals and steels can be traced in history back to the Bronze and Iron Ages, over ten thousand years ago. Many of the properties which appealed to primitive man are the same reasons for the universal usage of steel and its products today. Durability and a high strength-to-weight ratio, although probably not thought of in those terms then, are just as valuable today as they were in the year 8,000 B.C.

Fortunately there have been developments in the first iron and bronze products, and the methods used to join them. The welding of steel has become commonplace, and despite the fact that it has evolved from a technology developed only one hundred years ago [39], it has virtually replaced riveting and most other mechanical means of joining steel. This is not to imply that soldering, brazing, gluing and the mechanical fastening of steel are antiquated methods suffering an agonized death; methods for joining steel other than welding are still popular [59], and vital to many industries.

Technology is focusing upon improving the characteristics for steels and the methods used to join them, both through revolution, but more dominantly, through evolution. The strength level of 100 KSI has been exceeded by many types of steels, and in the case of titanium products, it has been doubled [26]. The problem with levels of strength that are so high is that it becomes increasingly more difficult to successfully weld separate pieces together as the base metal strength level increases. One of the most common maladies of modern high strength steel construction is weld cracking.

Before presenting the material forming the basis of this thesis, a background on weld cracking must be presented.

WELD CRACKING

Weld cracking is the result of permanent or transient high tensile stresses, and/or the material being excessively brittle. Weld cracks, once they have occurred, can frequently be discovered by methods as simple as a visual inspection using a dye penetrant or magnetic particle test, although more thorough, and costly, tests have been developed to expose cracks which elude the simple tests.

There are five classifications for the cracks resulting from welding; these in turn are separated by whether they are typically found in the deposited weld metal or in the base-plate.

Those cracks found in the weld metal can run parallel to the weld bead, called *Longitudinal* cracks, or intersect the weld perpendicular to the axis of the weld bead, called *Transverse* cracks, or begin near the center of the weld metal in any variety of shapes, called *Crater* cracks. Although a crack begins in the weld metal alone, this fact does not prohibit a crack, once started, from proceeding into the previously crack free baseplate.

The base metal can also experience cracking in the longitudinal or transverse directions. Depending upon the location of the crack, longitudinal cracks are classified as either *Toe*, *Root*, or *Underbead* cracks (Figure 1).

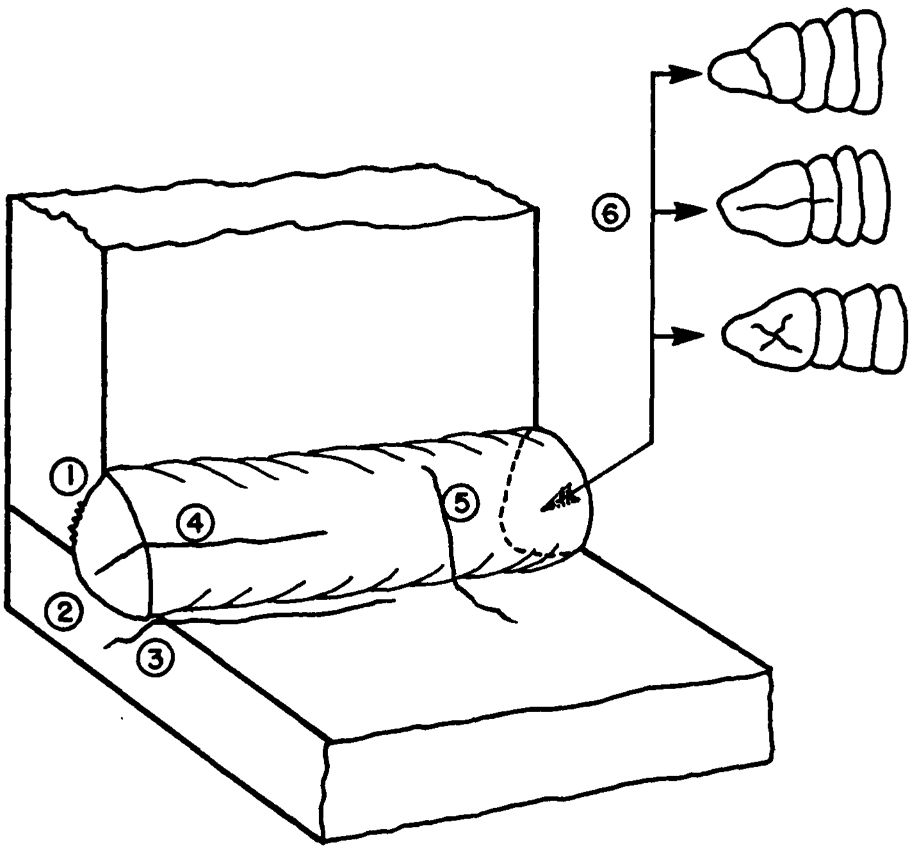
When a crack actually occurs determines whether the crack is a *hot* crack, or a *cold* crack. Hot cracks occur at temperatures very close to the solidification temperature of the molten weld metal pool. Cold cracks are those cracks which form at lower temperatures, usually below 400° F.

The mechanisms of hot and cold cracking differ significantly, and the welding engineer must be able to identify the causes of the failure before recommending the appropriate corrective action. If given a sample that has experienced cracking, but it is not known whether the cracks are the result of hot or cold cracking, there are several methods available to help classify the cracks.

HOT CRACKING

Macroscopically, hot cracks will usually have smooth surfaces near their tip, and if the crack is exposed to the atmosphere the surfaces will be oxidized. This type of oxidation forms very rapidly at elevated temperatures. Cold cracks typically are shiny, and if examined shortly after their formation, they will be free from oxidiation [17].

To help classify weld cracking, a microscopic examination of the crystal structure of the base metal, the weld heat affected zone (HAZ) and the weld metal should be performed. Although a single crack can be both transgranular (along the grain boundaries), and intergranular (passing through the



TYPICAL WELD CRACKS

① Root Crack

② Underbead Crack

③ Toe Crack

④ Longitudinal Crack

⑤ Transverse Crack

⑥ Crater Crack

Figure 1. Weld cracks by orientation and location

grains), most hot cracks form intergranularly. Conversely, cold cracking is predominantly transgranular.

Methods exist for comparing the tendency of different steels to crack. Most of the indicators used to determine cracking sensitivity are relative; thus although for a given situation steel *A* might demonstrate a better resistance to cracking than steel *B*, the test used will not indicate that *both* steels might crack.

As developed by M. Inagaki [29], and found in the text by K. Masubuchi [39], a formula that uses the percentages of the chemical composition which evaluates hot cracking is:

$$HCS = \frac{C\ (\ S + P + Si/25 + Ni/100\ ) \times 1000}{3\ Mn + Cr + Mo + V}$$

When the Hot Cracking Sensitivity (HCS) is held beneath 4 a steel is judged to have a good resistance to hot cracking.

Alternatively, if the below listed steel constituents are kept within the prescribed limits, hot cracking should not occur [29].

Sulfer	$< 0.035\%$
Nickel	$< 1.0\%$
Manganese	$< 0.80\%$
Carbon	$< 0.15\%$
Sulfer (%)	$< 35 \times$ Manganese (%)

Carbon equivalencies have been recommended by a number of different organizations [30], [39], [61] and individuals [24], [52], [31], and are used to evaluate cold cracking sensitivity in the same way that Inagaki's hot cracking sensitivity formula is used for hot cracking. Since there are so many different cold cracking carbon equivalencies none will be listed here. Appendix C further addresses carbon equivalencies.

The solidification temperature of a metal is the key to hot weld cracking. An elementally pure sample of metal will melt and solidify at a single temperature for any uniform set of testing conditions. When alloying elements are added to the initially pure sample, the metal mixture begins to melt and solidify over a range of temperatures. That range of temperatures becomes more pronounced as the amount of elements with different melting temperatures increases. As an alloy begins to cool from a homogenous liquid, grains form that contain a larger concentration of those elements that have the higher solidification temperatures. Conversely, the last liquid to solidify will contain a higher concentration of the alloying elements with the lower freezing temperatures. It is when the last liquid is turning into a solid that large stresses build up between the grains. The high stresses result from the shrinkage of the last molten metal as it freezes and is forced to bond to adjacent disconnected crystals.

Alloys which solidify over a short temperature range exhibit a reduced tendency to form hot cracks [39]; implying that weld joints which are closer to being elementally pure will perform better against hot cracking than joints containing significant amounts of alloying elements. It is important to recognize that a large range of freezing temperatures is not the only factor responsible for hot cracking. If high stresses do not build up during the cooling of the liquid metal, then cracking will not occur.

A generalized theory on hot cracking was presented by Kammer, Masubuchi, and Monroe [32] that suggests a four stage process in the solidification of a metal. The first stage is when there are solids and liquids mixed together, both capable of moving around within the pool, and is called the *Primary dendrite formation* stage. When a significant portion of the liquid has solidified, the solid portions are no longer capable of movement, but the liquid portions can still move freely; this is called the *Dendrite interlocking* stage. When enough liquid has formed into solid crystals, and the remaining liquid can no longer migrate, the *Grain boundary development* stage exists. When the sample is entirely solid, the fourth and final stage, *Solidification* has occurred [32].

Hot cracking is combatted best by carefully selecting the elements used in the manufacture of the base metal and the weld metal. The Hot Cracking Sensitivity equation identifies some of the most critical alloying elements.

COLD CRACKING

This work focuses particularly on cold cracking. Hydrogen has been recognized as a prime cause of cold cracking for over one hundred years. In the interim many theories regarding hydrogen cracking have been proposed, but as noted by

Papazoglou [44] and originally set forth by Savage *et al.* [48], they can all fit into one of four general classifications:

Planar Pressure theories

Surface Adsorption theories

Triaxial Stress theories

Dislocation theories

The Planar Pressure theories are based upon the premise that atomic hydrogen, which is highly diffusible, is produced as the steel temperature is lowered. The atomic hydrogen which is forced into the steel gathers in regions containing minor defects, such as pores or microvoids; here atomic hydrogen combines to form molecular hydrogen, which cannot diffuse through the steel. As the amount of molecular hydrogen increases the pressure builds up. Eventually, aided by any other stresses available, such as those due to tensile loadings, the hydrogen gas creates a crack. When a crack occurs, or is enlarged, it will continue to grow until the combined internal hydrogen pressure and internal and external stresses are insufficient to continue to propagate the crack. Atomic hydrogen will once again gather in the now enlarged defect (crack) repeating the process that led to the initial cracking.

In the Surface Adsorption theory, hydrogen diffuses to the surfaces of a preexistent crack, where it is adsorbed. At this point it has been proposed that the adsorbed hydrogen reduces the surface free energy, which when reduced enough will permit further crack propagation.

A. R. Troiano initially proposed that atomic hydrogen collects in regions in front of a crack tip or void where the magnitude of triaxial stresses are the largest [55]. Thus the name of the Triaxial Stress theory. In this theory there is a critical value of hydrogen concentration above the baseline interstitial concentration which when exceeded will permit hydrogen cracking. Troiano's initial postulate stated that hydrogen cracks are formed in a discontinuous fashion; as a result of the lower triaxial stresses at the new leading edge of the crack. Furthermore, in order for the crack to continue propagating a time delay is necessary, during this delay the triaxial stresses build up in concentration until they once again surpass the critical value required for cracking.

An article written by R. A. Oriani in 1970 disagreed with Troiano's explanation of what causes a crack to sometimes be generated in a discontinuous process [45]. Oriani suggested that cracks, in and of themselves, form all at once without pause. Although observations have demonstrated that cracks do not form in a continuous process, Oriani attributed this characteristic not to the crack, but to inconsistencies within the steel.

The final set of theories fall into the class of Dislocation theories. These can be further divided into two subcategories.

The first subcategory suggests that fracture is accelerated by the absorption of hydrogen, which stimulates plastic deformation. As originally proposed by C. D. Beachem [12] the manner in which the plasticity was affected was not specified. Additional work accomplished by J. A. Clum with ion microscopy has theorized that hydrogen may reduce the work required to nucleate dislocations at the metal surface and is thus responsible for the plastic deformation [17].

The other subcategory supports an explanation that hydrogen dislocation interactions suppress glide, and provide the means for producing large local accumulations which induce subsequent embrittlement and cracking [54].

Cold cracking caused by the presence of hydrogen requires the concurrence of four provisions. Those conditions are [18]:

The presence of hydrogen - Nearly impossible to totally exclude from a welded joint, it is most commonly introduced into a weld by the disassociation of water into atomic hydrogen and oxygen. Once present in the atomic form, the hydrogen is absorbed by the molten weld pool, and later diffuses to the HAZ.

Tensile stresses acting upon the weld - External tensile stresses are caused by the joint design and loading. Internal tensile stresses result primarily from the shrinkage of the weld metal as it cools.

The presence of a susceptible microstructure in the HAZ or weld metal - The molten weld metal causes part of the HAZ microstructure to cycle from ferrite to austenite and back to ferrite. Those portions of the microstructure are vulnerable to hydrogen embrittlement. Historically cracks caused by hydrogen are found in those portions of the HAZ that have undergone a microstructure transformation.

Low temperature - Cracking usually does not occur in any steel above 250° C (482° F), or structural steels when the temperature is greater than 150° C (302° F). It is this trait that has generated the term "cold" cracking. Since there is a delay in time before the steel temperature is reduced below the above thresholds, this type of cracking is also known as "delayed" cracking.

CONTROLLING COLD CRACKING

There are several variables contributing to, and several methods for controlling each of the four prerequisites of cold cracking. Effectively removing only one of the four has the same effect as removing either the fuel, the oxygen, or the heat from the classic "Elements of a Fire" triangle; the process breaks down.

Hydrogen is introduced into the weld metal by one or two sources; either the welding consumables including the surrounding atmosphere, and/or the material to be welded itself. The cleanliness of the surfaces to be welded cannot be emphasized enough. Dirt, hydrocarbon compounds such as oils, and grease, degreasing fluids, or residue from *Tempil* sticks, or coatings such as oxides or paints all break down and release atomic hydrogen when subjected to the intense heat produced by welding.

Similarly moisture, which disassociates into atomic hydrogen, is frequently absorbed by the weld rod coatings or welding fluxes. This is because they are so low in intentional moisture that they act like a desiccant. This problem can be reduced by using low hydrogen electrodes, such as an E-11018, and by following the manufacturer's recommendations for time exposure to the atmosphere once the electrode is removed from its hermetically sealed shipping container. The American Welding Society and the United States government have established moisture content specifications as follows[40]:

Electrodes	Maximum moisture content, percent
E7015, E7016, E7018	0.6
E8015, E8016, E8018, E9015, E9016	0.4
E9018, E10018, E11018	0.2

When E70XX or E80XX electrodes are used as a substitute for tack and root pass welding in lieu of E90XX and E110XX electrodes, they should be baked until the moisture content is reduced to 0.2 percent [40].

When translated to a maximum exposure time recommended to keep the entrained moisture content below 0.2 percent, the following exposure times should be observed [40]:

Electrode	Maximum exposure time in hours
E70XX	4
E80XX	2
E90XX	1
E110XX	1/2

Here again when E70XX or E80XX electrodes are substituted for E90XX or E110XX electrodes for tack and root pass welding, the maximum exposure time is to be reduced to 1/2 hour [40].

The storage of opened electrodes in portable rod ovens, and the procedure of rebaking the electrodes if they have been exposed to the atmosphere for an excessive length of time also help to minimize moisture pickup by the electrodes (Figure 2). Naturally the relative humidity of the atmosphere will be a determining factor in the absolute rate of moisture pickup by the electrode. As a general rule, electrodes can be rebaked only once.

Low hydrogen welding electrodes should never be exposed to rain, snow, or any other direct moisture.

Welding materials are also susceptible to the same mishandling as the steels which are to be welded. It is not uncommon to find grease and dirt on the tips of weld rods which are temporarily stored in a welder's pouch. Spooled welding wire can gather dirt when used in industrial areas; this dirt in turn can be transferred to the weld pool. Even a dirty welding tip is a potential source of contamination.

Not all of the hydrogen available at the time of the weld ends up in the workpiece. In actuality, much of the hydrogen escapes into the atmosphere (Figure 3). After the weld metal has been deposited, some of the hydrogen that has been included in the weld bead will actually diffuse out of the work. The quantity of hydrogen that does escape the weld is dependent upon the initial absorbed hydrogen level, the geometry of the welded joint, and the cooling rate of the workpiece.

Postheating the weld area serves two purposes: it is primarily used to relieve internal stresses that are built up

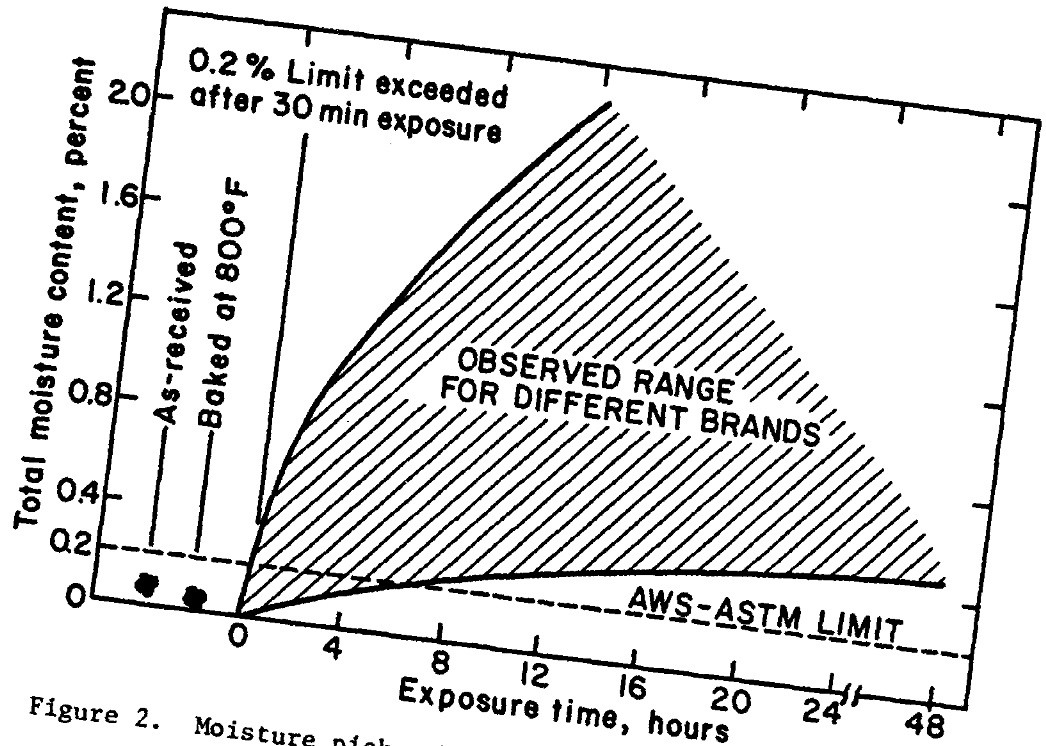


Figure 2. Moisture pickup by E11018-G electrodes exposed to an atmosphere of 90% relative humidity at 75°F [39]

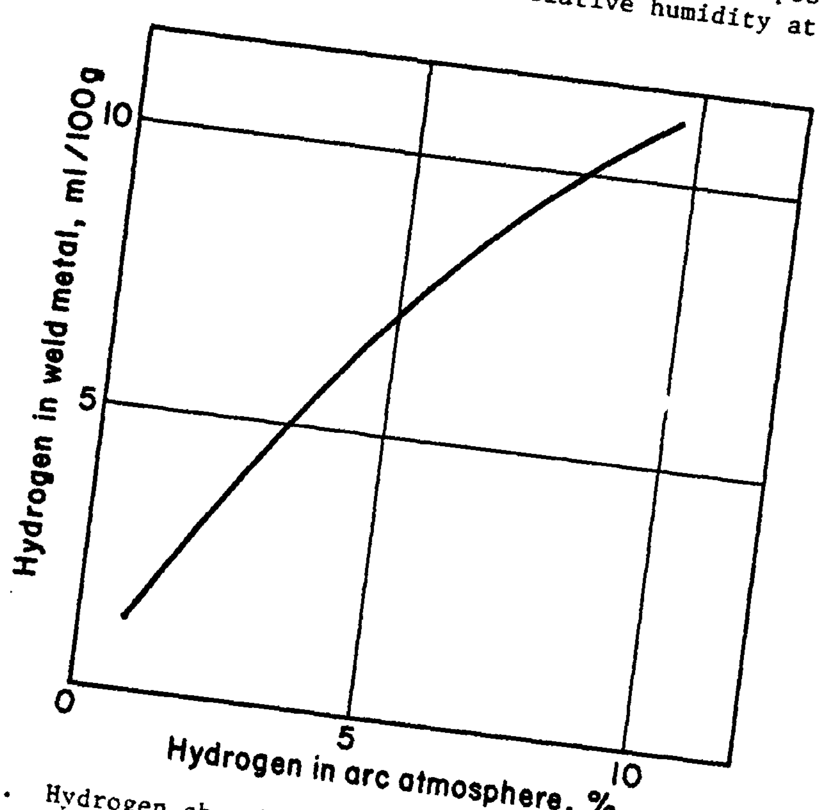


Figure 3. Hydrogen absorbed by molten weld pool increases as the concentration in the surrounding atmosphere increases [18]

due to the welding process, but it has the added benefit of increasing the solubility of the remaining hydrogen in the steel (Figure 4).

Depending upon which welding process has been selected, the hydrogen level at the time of welding can be reduced even future. The work by F. R. Coe entitled "Preventing Delayed Cracks in Ship Welds - Part II" has an excellent appendix relating potential hydrogen levels to the processes and materials used. Figure 5 compares the relative hydrogen levels for different welding processes and electrodes.

As described previously, welding stresses are the result of either internal or external forces. When welding two pieces of metal together it is virtually impossible to joint them without causing the temperature to cycle in the region around the joint. Thermal stress are built up as a result of the uneven temperature cycling of the baseplate. These stresses are further aggravated by multiple pass welding techniques, where the steel is heated and cooled repeatedly. Figure 6 shows how the stresses and temperatures would typically vary along a weld line based on the relative position of the molten weld region. After the welded portion has totally cooled, as indicated by cross-section D-D, residual tensile and compressive stresses remain. The distance from the weld centerline to where the stresses change from tensile to compressive is called the half width of the Tensile Residual Stress Zone (TRSZ). The absolute size of the TRSZ is directly related to the heat input, h, and inversely related

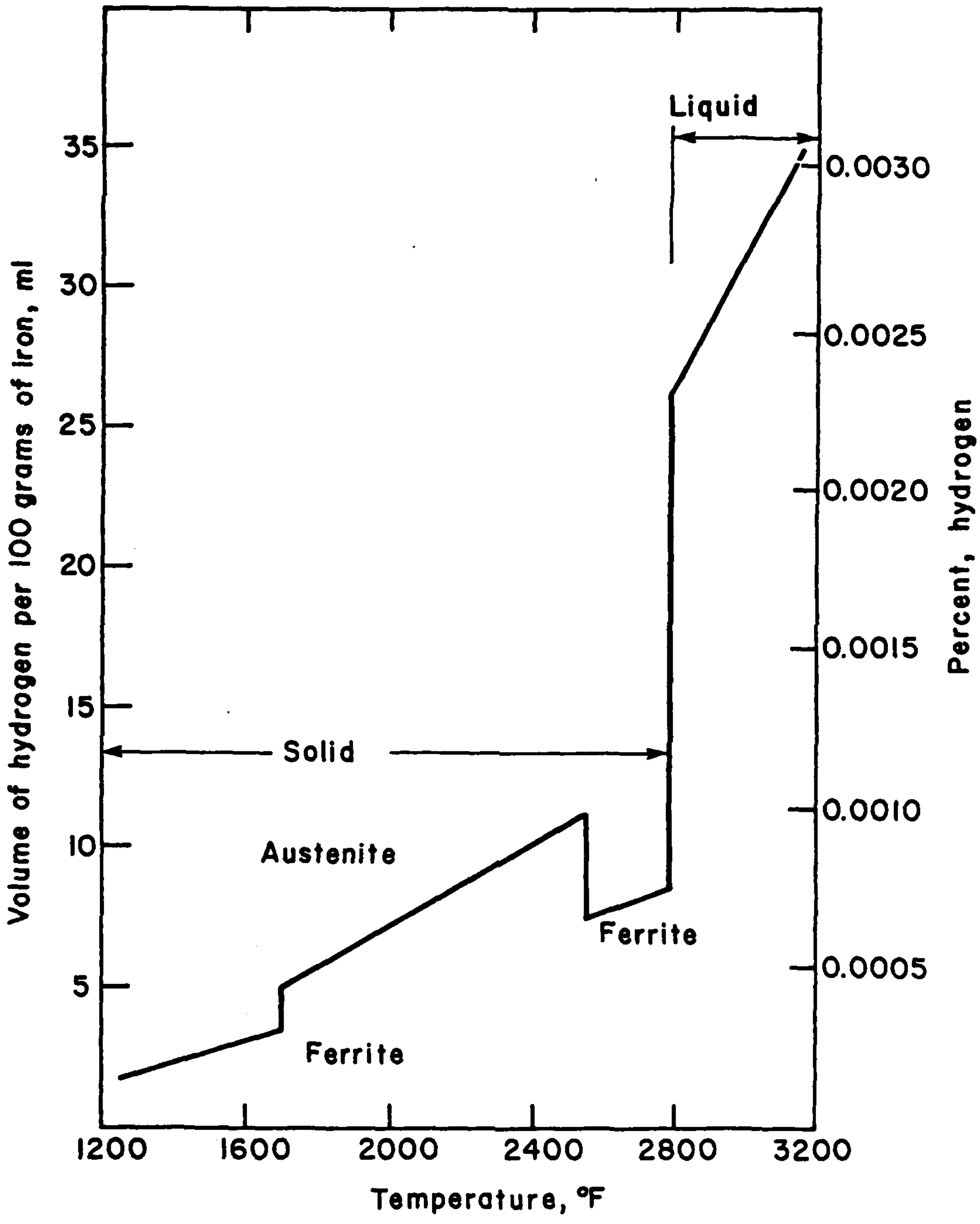


Figure 4. Solubility of hydrogen in iron [40]

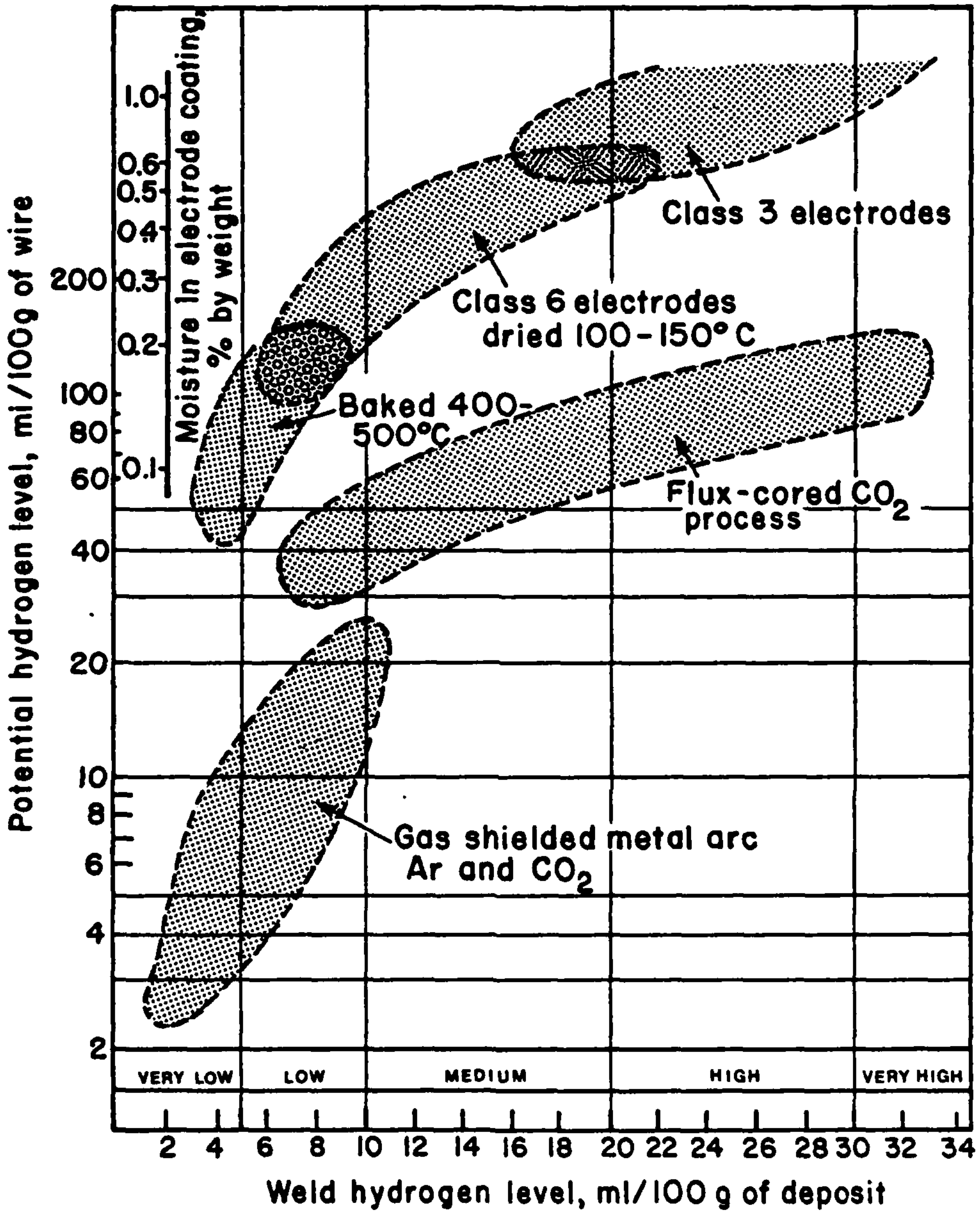


Figure 5. Relationship between potential hydrogen and weld hydrogen [18]

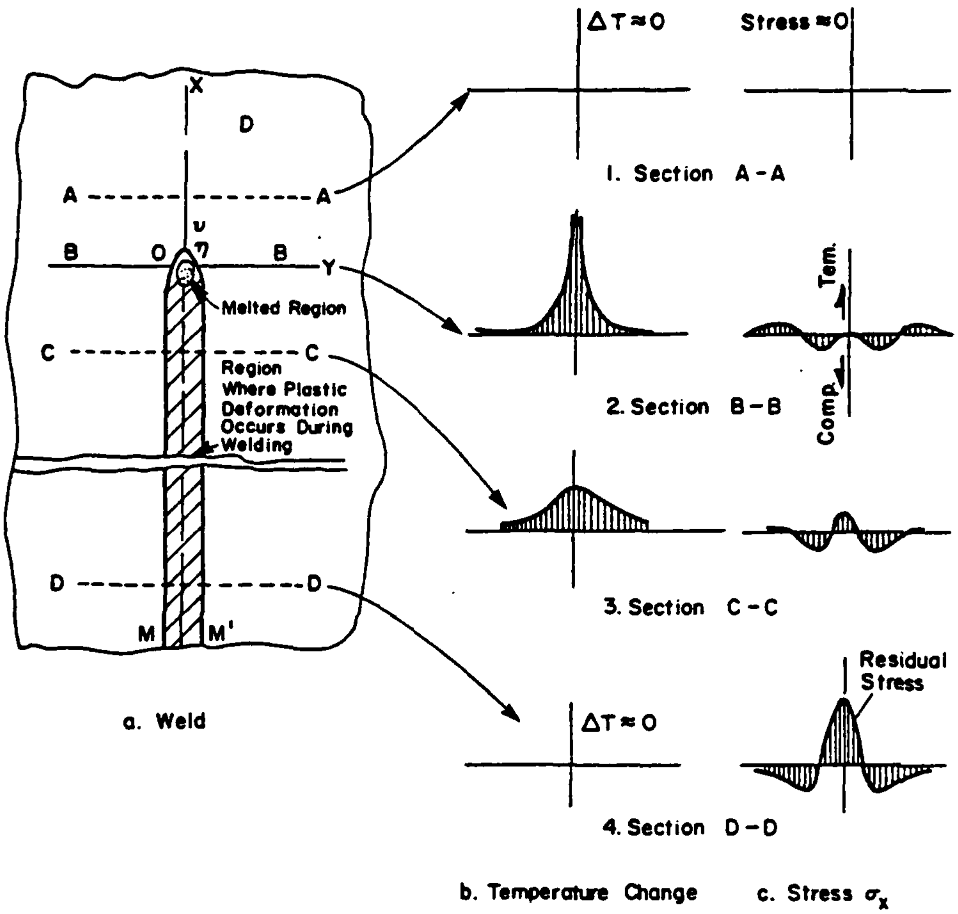


Figure 6. Schematic representation of changes of temperature and stresses during welding [39]

to the welding speed, v. (See Figure 7)

The amount of welding heat input and the use of preheating must be carefully monitored. If the cooling rate of the steel becomes excessive, the HAZ hardness increases. Thus if the heat input is lowered too far, the HAZ will become hard and susceptible to cold cracking. When the cooling rate is slowed in an effort to alleviate the problems of a hard HAZ, the notch toughness of the joint decreases. The loss of notch toughness is especially detrimental to quench and tempered steels which have gained their strength and toughness by rapid cooling.

External stresses can be caused by a number of factors; however, most are the result of poor fitup. The sequence used when welding is very important. If a large cylinder was cut into two smaller cylinders, and then welded with a continuous bead, by the time the two ends were about to be joined they probably will not match up correctly. There are many possible causes for this phenomenon, including asymmetrical heat input across the joint, asymmetrical part mass density, different coefficients of expansion (If two different materials are used), and partial insulation of one side of the joint. The simplest solution is to weld the cylinders together using short welds in a staggered arrangement which would join the cylinders in the same fashion that the lug nuts are tightened on an automobile wheel. While this will reduce the amount of distortion at any one point, permitting the cylinders to be joined with a minimum of obvious mismatch, it will form

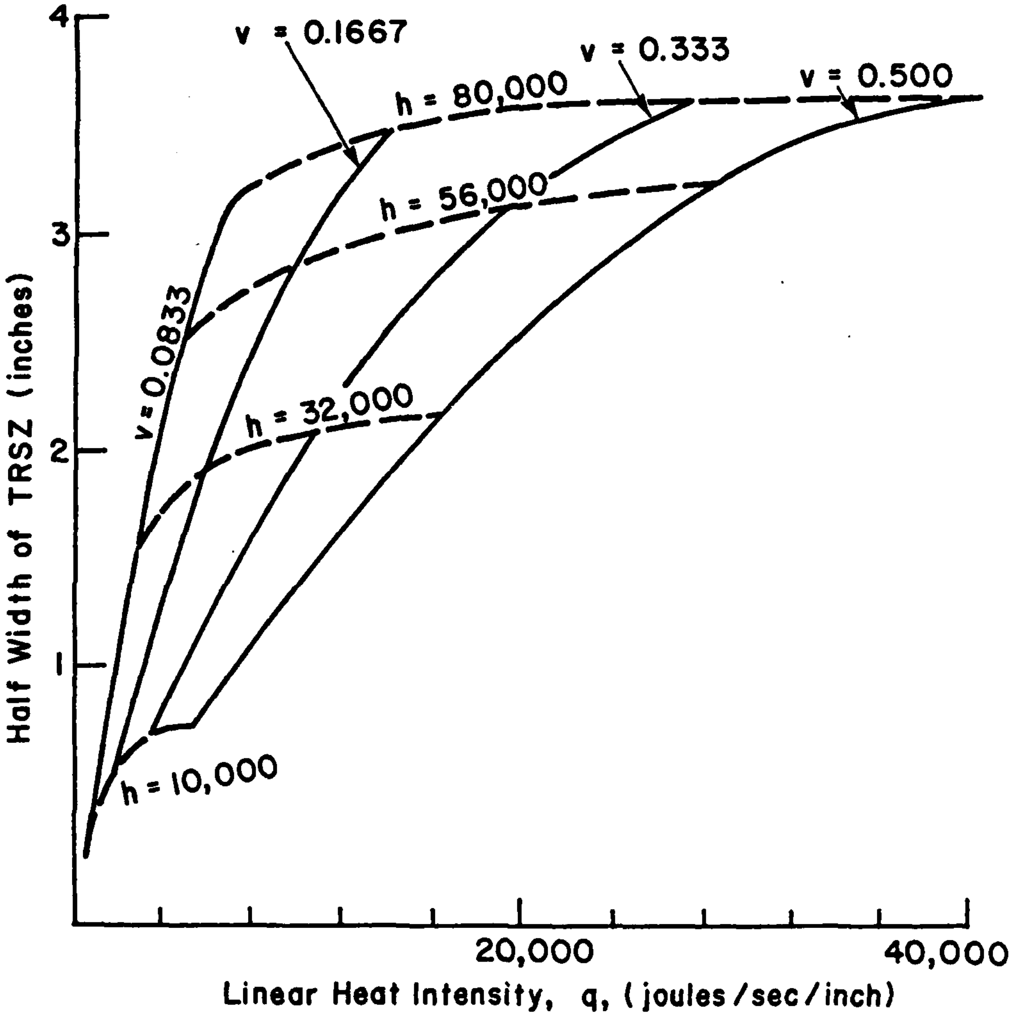


Figure 7. Effects of linear heat intensity, q, and welding speed, v, on the width of the tensile residual stress zone [39]

stresses of varying magnitude along the entire weld line. The advantage with this method is that while the total stress amount remains the same, it is no longer concentrated in the last portion welded. Instead the stresses are more evenly distributed around the entire circumference. Certainly it would have been better to have properly designed the joint so that no stresses resulted from the welding process, but in this situation lowering the absolute magnitude of the stresses will minimize the possibility of a catastrophic failure.

As an extension of the last example, Kihara *et al.* [34], [35] examined how the welding sequence would affect the shrinkage of a slit weld divided into three sections of equal length. They found that the lowest maximum shrinkage occurred when the middle section was welded first, followed by the welding of the right and left portions respectively. Conversely the specimen which had the left, then right and finally the center sections welded experienced the largest amount of shrinkage.

Stress raisers are the result of an abrupt change in the weld shape or a defect in the weld, and they are the point where stresses accumulate. Slag inclusion, inadequate root penetration, and undercut are stress raisers that are the result of poor workmanship and/or poor welding technique. The previously described example of poor fitup will result in a stress raiser, and could be the result of an improper design.

The loss of the *USS Ponagansett* in Boston Harbor in late 1947 deserves inclusion in the "For-the-lack-of-a-horseshoenail-the-kingdom-was-lost" category. The *Ponagansett* split in two alongside the pier because of a fracture which initiated at a stress raiser caused by an arc strike [48].

There is little quantifying data for the various external stress contributors. It has been found that when the root gap exceeds 0.016 inches there is a significant increase in the likelihood that joint cracking will occur [18]. Furthermore, the shape and design of the weld root can impact dramatically upon the elastic stress concentration factor. The elastic stress concentration factor is equal to the ratio of the local stress at the root of the weld to the average reaction stress (net stress of the weld cross-section).

Table 1 compares the relative levels of elastic stress concentration factors and is excerpted from a publication written by R. A. J. Karppi [33]. It can be observed that the stress level can be reduced by more than half by selecting a better suited joint geometry.

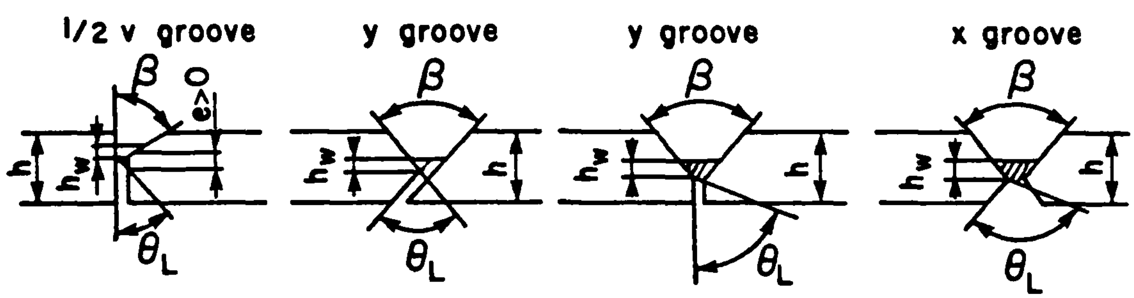
There are two ways in which residual stresses can be reduced or removed; they are thermal stress relieving methods, and mechanical stress relieving techniques.

Preheating is frequently used in order to help reduce the total temperature differential in the areas adjacent to the weld. By doing this, the stresses remaining after the joint is completed are reduced. Thermal stresses can be relieved by annealing the part in question, and while this is a valuable method for small pieces it is impractical if not impossible for larger assemblies. Thermal stress relieving cannot be

Table 1

No.	Variable	Groove type	Groove angle $\beta(°)$	Root angle θ	Thickness h(mm)	Eccentricity η	Throat thickness h_w(mm)	K_t
		GEOMETRIC CONFIGURATION OF GROOVE WELD						
1				40				6.5
2		1/2V	60	60	30	0	5	5.8
3				90				4.8
4	Groove type			100				4.7
5		y	60	114	30	0	5	4.0
6	Root angle			120				3.5
7				80				4.7
8		Y	60	90	30	0	5	4.2
9		X	60	120	30	0	5	3.7
10					20			5.3
11	Plate thickness	1/2 V	60	60	30	0	5	5.8
12					50			6.0
13							5	6.0
14	Throat depth	1/2 V	60	60	50	0	7	7.2
15							9	8.0
16						0.5		6.9
17	Eccentricity	1/2 V	45	60	30	0	5	5.4
18						-0.5		3.5

Eccentricity η = 2eth, see below



used without due regard to its effects upon the microstructure, tensile and impact strengths of the steel.

The process called Controlled Low Temperature Stress Relief was specifically developed for those assemblies which were too large to stress relieve by normal thermal stress relieving techniques. This process heats the metal on the adjacent sides of the weld bead, while keeping the weld itself relatively cool. This has the affect of thermally expanding two compression zones to the a point where the the tensile stress in the weld is above the yield point. Upon cooling the metal will contract, reducing the stresses below the yield point [39].

Controlled low temperature stress relief has not been universally accepted as an effective stress removal tool. However, there have been results where both the longitudinal stresses and the transverse residual stresses have been reduced. In these cases, the transverse stresses have been reduced by as much as 60% [39].

When an engineer is considering the usage of controlled low temperature stress relief, it must be realized that the metallurgical properties of the weld metal and heat affected zone will not be improved.

The two most popular mechanical stress relieving processes are Vibratory Stress Relieving, and Peening. Neither of these procedures will alter the microstructure of the workpiece and must be a consideration when selected for stress relieving.

Peening is the mechanical striking of the metal with a hammer. Peening has several advantages and disadvantages, therefore when used it should be done judiciously.

From the detrimental aspect, peening may conceal defects, or even produce some by either perforating thin sections, or creating notches in the metal. Peening has also been known to actually extend cracks that already exist, and it may also be responsible for a reduction in the notch toughness of a piece of metal which will not be heat treated later.

Peening can be useful, otherwise it would not have developed into an acceptable stress relieving process. Peening can be used to reduce distortion, and residual stresses. in order to obtain these beneficial aspects of peening, each weld pass in a multipass joint must be peened. Otherwise the positive affects of peening the last weld pass are obliterated. A final benefit which may be gained by peening is an increase in fatigue strength due to the addition of compressive stresses near the surface of the joint, distant from the joint's neutral axis.

Vibratory stress relieving uses both high and low frequency vibrations which is transformed into mechanical energy. The welded region experiences a hammering sensation from an attached wave generator.

The region to be stress relieved must experience plastic yielding locally in order for the treatment to be effective; this may be achieved through the excitation of the part at its natural frequency, but this is not easily achieved and maintained. Vibratory stress relieving techniques may not fully remove all of the residual stresses, but even a reduction in the stress levels will aid the structure.

Vibratory stress relieving methods have not met with full approval by experts in the field, and until it is fully proven to be effective, it will not become a major stress relieving technique.

The third simultaneous condition required for cold cracking is a susceptible microstructure in the heat affected zone.

Although it has been mentioned several times and its name is self explanatory, the best method to determine the extent of the heat affected zone is to make a cross-sectional examination of the welded portion. When a cross-section is polished and etched the HAZ is readily discernible as it is a different color than either the weld or the parent metals and it appears to form a ring around the weld metal.

The effect of the molten metal is to raise the temperature of the region called the HAZ. As the cooling rate increases, the grains of the metal become increasingly more coarse and become martensitic. The grains remain coarse because they cool very rapidly, and do not undergo the same metallurgical processes that the base metal has received.

The coarser grains are found in the areas that are the hardest. As a compensating effect, the regions with the greatest hardenability also have the least ductility. It is due to the decrease in ductility and increase in hardness that these regions become brittle, and suffer the greatest possibility for cracking.

In ferritic steels, five primary regions (R-1 through R-5) are formed in the HAZ. The relationship of the regions to the iron-carbon phase diagram is illustrated in Figure 8. The characteristics of the regions are as follows [20]:

R-1 - Weld interface (fusion line), partial melting occurs in this region.

R-2 - Base metal temperature exceeds the A_3 temperature, austenitization and grain growth occur before cooling.

R-3 - Temperature still above the A_3 point, permitting austenitization, but not high for austenite grain growth.

R-4 - Temperatures between the A_3 and A_1 points occur, resulting in differing amounts of partial reaustenitization.

R-5 - Overaged (overtempered) region, where the maximum temperatures reached are just below the A_1 temperature.

Figure 9 illustrates the HAZ microstructure for a high strength low alloy steel that results from single and multiple weld passes. The following description comes from a report to the Federal Highway Administration by Davidson *et al.* [20].

> In multipass welding, thermal excursions into the intercritical temperature range can further reduce the toughness in the coarse grain HAZ. Regions exceeding temperatures above the A_{c3} are designated by the letter A. Regions reaching temperatures between A_{c3} and A_{c1} are designated by the letter B, and regions reaching temperatures below A_{c1} are designated by the letter C. Overlap

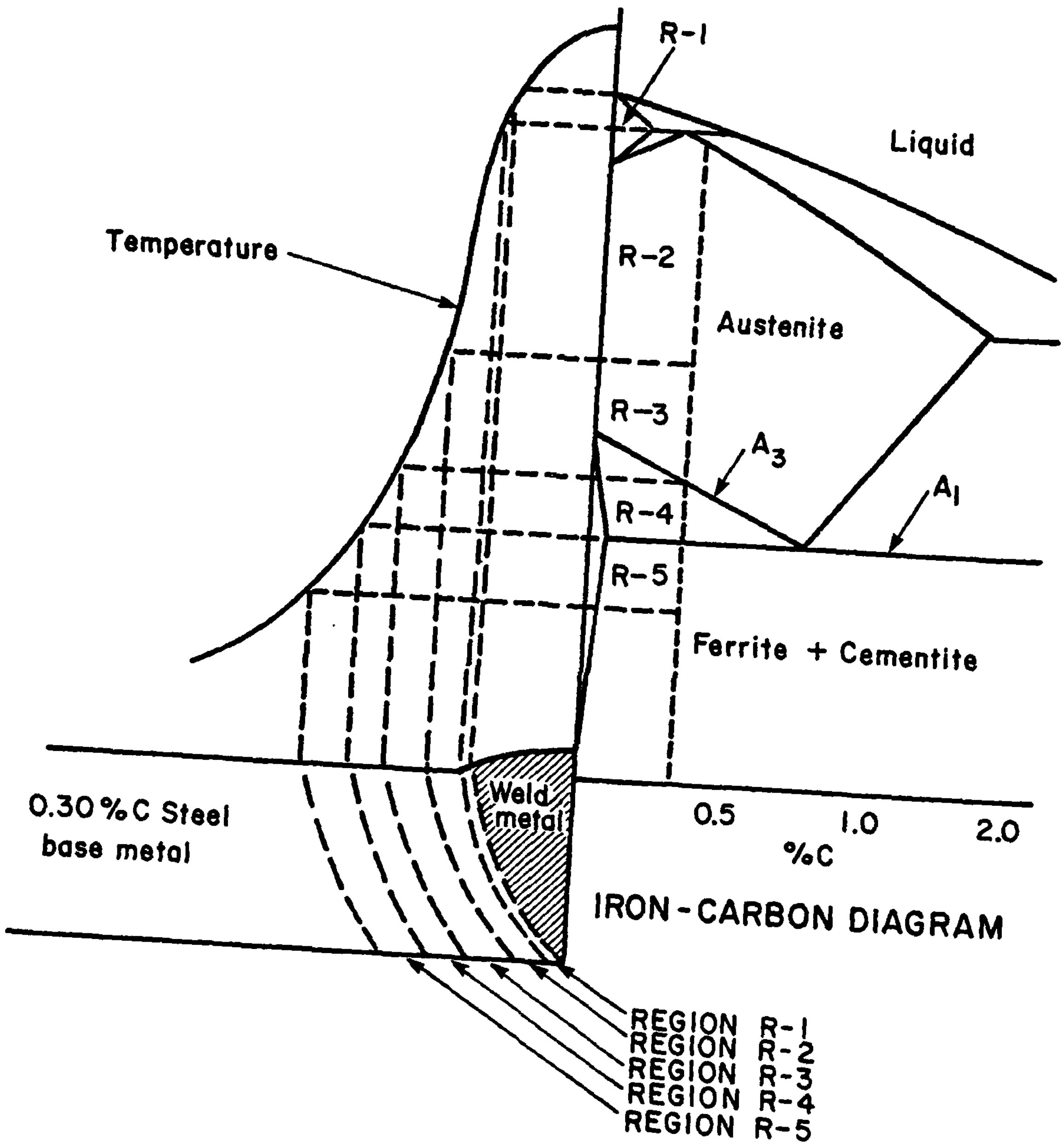
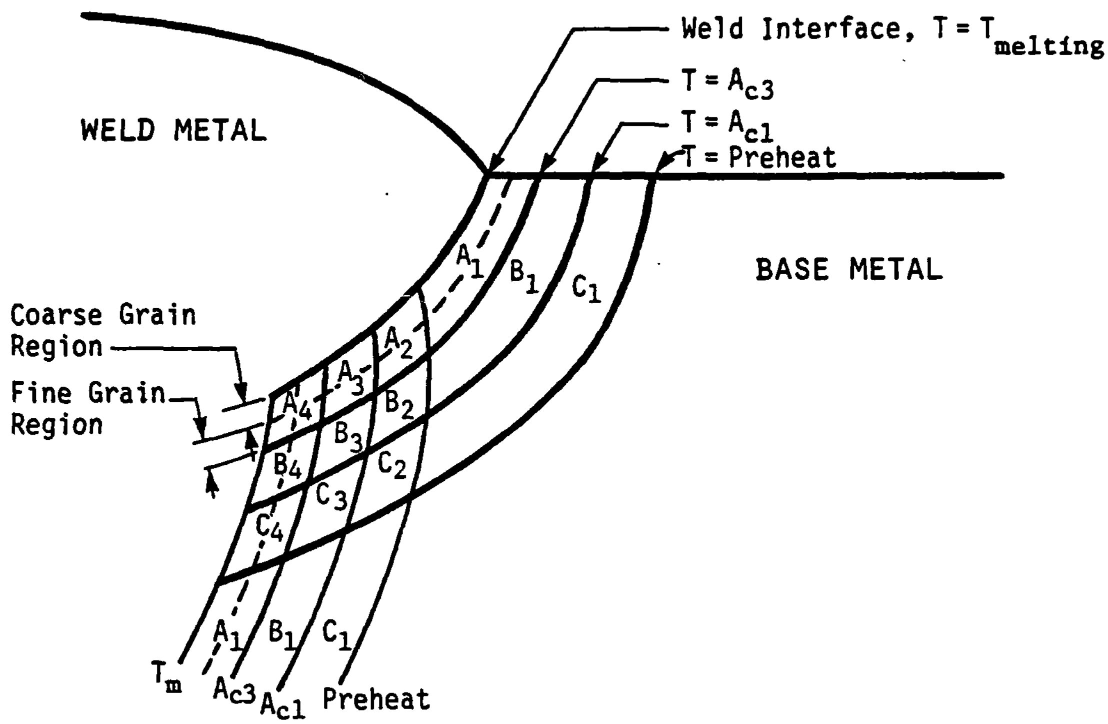


Figure 8. Correlation of peak temperatures in a weldment with the iron-carbide phase diagram [20]



REGION	DESCRIPTION
A_1	Coarse and fine grain fully transformed structure of martensite, bainite, or both. Untempered except for any self-tempering which may occur from a relatively high M_s temperature.*
B_1	Finer grain, partially transformed (intercritical) region, transformed portion untempered.
C_1	Tempered or overaged region.
A_2, A_3, A_4	Similar to A_1.
B_4	Coarse and fine grain, partially transformed region containing relatively high carbon martensite and tempered ferrite.
C_4	Structure A_1, tempered.
B_3	Similar to B_1, but with additional partial transformation.
B_2	Similar to B_1.
C_3	Similar to B_1 but tempered
C_2	Similar to C_1, but additional tempering.

*Depending on the weld bead size and weld energy, Region A_1 may occur repeatedly along the weld interface.

Figure 9. Location and description of various regions in a weld HAZ for an HSLA steel [20]

of these regions due to subsequent weld passes results in subregions being formed described by the various subscripts. Regions B_4 and A_1, A_2, A_3, and A_4 would be expected to exhibit the poorest toughness. Low toughness would be expected in Region B_4 because of the the large grain size and high carbon martensite that forms in the remaining austenite during partial reaustenitization. Regions A_1, A_2, A_3, and A_4 (last-pass regions) would exhibit relatively low toughness because of the large grain size and lack of tempering from subsequent weld passes (similar to that of a single pass weld). Regions similar to B_4 would be expected to exist in the HAZ produced from each weld pass except the last. Moreover, the low toughness region A_1, may also occur repeatedly along the weld interface line depending on the weld bead size and energy input.

Methods for decreasing the grain size include decreasing the cooling rate of the welded region; this can be easily accomplished through the use of adequate preheat. The thermal mass of the plate, which is directly related to its thickness will also impact upon the rate of cooling. If a large thick plate has not been properly preheated, the remaining relatively cool and large mass will cool the welded portion rapidly. In order to prevent excessive cooling rates, minimum preheating temperatures are usually recommended by steel manufacturers. The testing described in Chapter IV details the examination of a high strength low alloy steel (HSLA) which requires significantly less preheating than conventional steel sections in order to be equally effective against delayed cracking. For normal steels, the general rules for minimum preheating listed below have had favorable results in combating cold cracking by assuring a resistant microstructure exists in the HAZ [40].

Plate Thickness (inches)	Preheat Temperature Required to control the Heat Affected Zone Microstructure (°F)
Under 1	75 minimum
1-2	125 minimum
Over 2	225 minimum

For multipass welding, the possibility exists that the temperature of the steels to be joined could drop below the preheat temperature. In those instances interpass heating is used to ensure that the steel retains an adequate amount of heat energy.

The welding process itself adds a significant amount of heat energy to the structure being joined, and the amount of heat added will also affect the cooling rate of the weld region. Heat input can be calculated using slide rules distributed by steel manufacturers, or by the use of the following equation:

$$\text{Heat Input} = \frac{\text{Welding current} \times \text{Arc voltage} \times 60}{\text{Welding speed}}$$

When the welding speed is expressed in inches per minute, and the welding current is in amps, the heat input will be in terms of joules per inch.

Heat input can be easily varied by adjusting either the numerator or, more effectively, the welding speed from the above equation. Furthermore, adjusting the arc voltage or current will alter the characteristics of the arc and the resulting bead shape. For Gas Metal Arc Welding, as the arc voltage is increased, the filler metal transfer mode will change from the "short circuiting" type, to the "spray" type. Although the arc voltage and current are directly related to each other, the short circuit transfer mode generally uses voltages between 12 and 22 volts, while the spray transfer mode uses voltages between 25 and 30 volts. Increasing the electrode diameter will have the effect of increasing the required welding current. Special welding techniques such as "weaving" have been developed to increase the welding heat input, while minimizing the welding rate.

The cooling rate is also dependent upon the welding process selected. Gas Tungsten Arc Welding (GTAW), Gas Metal Arc Welding (GMAW), and Shielded Metal Arc Welding (SMAW) are all relatively rapid cooling welding processes, while Submerged Arc Welding (SAW) is a medium speed cooling process, and Electroslag Welding (ESW) is a slow speed welding process [47]. (See Figure 10) Except for the extremely fast cooling rates, the toughness of C-Mn steels, both with and without carbide forming additives, decreases as the time required to cool to a preset level increases. The crack tip opening displacement (COD) was used to measure the magnitude

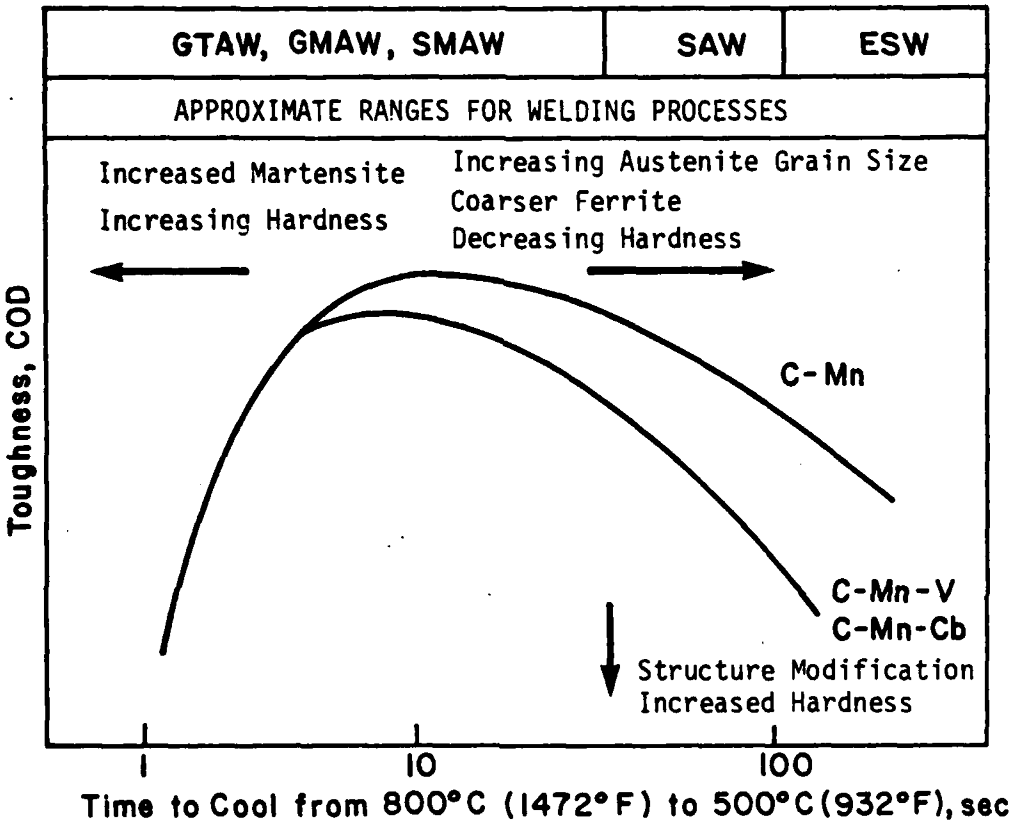


Figure 10. Influence of microstructure, composition, and welding process on HAZ toughness [49]

of the steel toughness in Figure 10.

When welding quenched and tempered steels, the amount of heat input used should not exceed 45,000 joules per inch for steel less than one half inch, or 55,000 joules per inch for steels thicker than one half inch. Exceeding these recommended values may adversely affect the steel's microstructure.

Postweld treatments, such as stress relieving by any method that acts upon the microstructure, can reduce the grain coarseness. Reducing the grain size has the effect of reducing the hardness of the metal, and increasing its ductility. F. R. Coe suggested that the use of a large weld bead or a thin plate will also act favorably upon the HAZ microstructure [18].

Although they are never intended, accidental arc strikes should always be avoided. As previously described, the *USS Ponagansett* experienced total failure due to an arc strike. Arc strikes are extremely short in duration. When an arc strike occurs, it heats a very minute amount of steel above the melting point, which cools extremely rapidly when the arc is broken.

Arc strikes create preferential crack initiation sites due to the heat interactions with the microstructure. The only way to prevent accidental arc strikes is to be careful. Once an accidental arc strike has been formed, the area affected must be ground clean to a minimum of 1/32 of an inch below the metal surface to remove the entire heat affected zone.

A low temperature is the final ingredient required for cold cracking to occur. The previous sections detailing the hydrogen level, the stress levels, and the type of microstructure necessary for cold cracking, have all made reference to methods for controlling the temperature of the welded steel.

As a review, the importance of the steel temperature lies predominantly in its impact upon hydrogen diffusion. In the work done by Coe, it is shown that as the temperature of the steel increases in the range of 20 - 150° C, the rate at which hydrogen diffuses through ferritic steel increases substantially. The cooling rate of the steel responds to the amount of preheating, interpass heating, postheating and the welding process heat input. Increasing any of the four contributors to the cooling rate will aid in the diffusion of entrained hydrogen, but caution must be observed so as not to alter the properties of the parent metals.

Tempil sticks are crayons which melt at a predetermined temperature, and can be applied to a piece of steel in order to monitor its temperature as it is being heated. The use of *Tempil* sticks or other temperature indicating crayons is a great aid for a rapid determination of the steel temperature, without the use of complicated thermocouples or other mechanical measuring devices. Additionally, *Tempil* sticks can be used as a quick check to verify that a piece of steel has not cooled below a predetermined temperature. Caution must be exercised when using temperature indicating crayons to keep them from getting too close to those areas which might be melted by the actual welding process. As described previously temperature indicating crayons can unintentionally add hydrogen into the weld.

Cold cracking is the result of many interacting events, Figure 11 relates how the various factors affecting cold cracking are interrelated.

HIGH STRENGTH LOW ALLOY STEELS

The many precautions and procedures used in welding normal structural steels are extremely costly and labor intensive. As a result, industry is continually searching for new products to replace structural steels. New composite products, such as graphite epoxies, are being developed at a whirlwind pace. Concrete can be formed into practically any shape, without the need for discontinuous joints, thus it is probably one of the highest strength, easily formed building products available today. In order to gain a larger portion of the construction and related markets, steel producers are constantly searching for improvements to their products which will both increase their demand and make them indispensable.

Attention in the steel industry to HSLA steels has increased dramatically in the past few decades. New manufacturing processes, the promise of better formability with reduced cracking characteristics, lower consumer costs, and the prospect of higher yield strengths have all added to the expanding interest in HSLA steels.

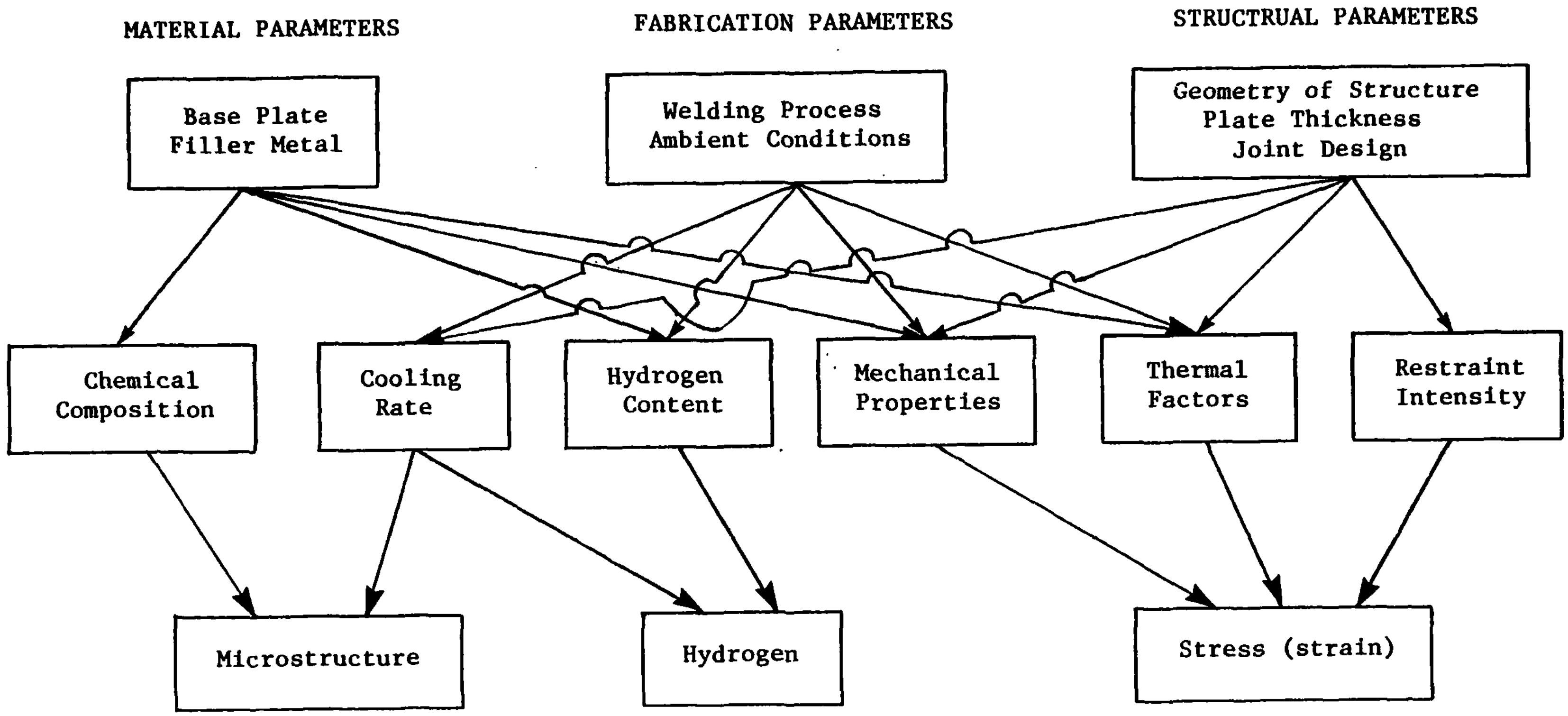


Figure 11. Factors that contribute to hydrogen induced cracking and their interrelationships [44]

Recently manufactured HSLA steels have demonstrated a strong resistance to delayed cracking, and the historical problems of weldability and formability appear to have been reduced to a point where they no longer are of prime importance.

High strength low alloy steels are not new to the market, they have been available since 1933, but they have yet to be given a precise definition. The American Iron and Steel Institute (AISI) gathers statistical information regarding domestic steel production and consumption. At this time their definition for an HSLA steel is:

> "High strength low alloy steel comprises a specific group of steels with chemical compositions specially developed to impart higher mechanical property values and greater resistance to atmospheric corrosion than are obtainable from conventional carbon structural steels containing copper. High strength-low alloy steel is generally produced to mechanical property requirements rather than to chemical composition limits.
>
> "High strength low alloy steel generally is intended for applications where savings in weight can be effected by reason of its greater strength and atmospheric corrosion resistance and where better durability is desired." [6]

The above definition has a great degree of latitude within it, and allows the steel manufacturer the choice of declaring whether or not a steel is an HSLA steel. The statistical confusion will not be alleviated in the near future if the new definitions for HSLA steels are implemented in January 1985 as currently proposed by the AISI.

The new proposal breaks steel down into five grades, which would be applicable for all AISI statistics. Carbon steels would be broken down into *High Strength Steels* and *Other Carbon*, while alloy steels would be classified as *Stainless*, *Weathering Steels*, or *Other Alloy* [6].

It is the opinion of some metallurgists that most of the HSLA steels manufactured will be lost in the *Other Alloy* category [16]. This is because *High Strength Steels* will be those <u>carbon grade steels</u> with an <u>ordered</u> minimum yield strength of:

All products other than tubular - 42 KSI

Tubular products - 56 KSI

While *Weathering Steels* will be limited exclusively to those steels ordered for their weathering characteristics, such ASTM A588 and A242. *Other Alloy Steels* will be those alloy steels that do not comply with the definitions of stainless or weathering steels, and contain more than a prescribed percentage by weight of any of 15 specified elements. This author has yet to find a currently manufactured HSLA steel, which is not a weathering steel, that does not fall into the *Other Alloy Steels* category. As an example, the popular steel grades of HY-80 and T-1 will fall into the *Other Alloy Steels* category.

New HSLA steels can achieve their strengthening by any number of processes.

Micro-alloying techniques, make use of elemental additives for micro-alloying such as Boron, Calcium, Columbium (Niobium), Titanium, Vanadium, Zirconium, and other rare earths. The quantity of these purposefully added elements is usually kept below 0.10% each. The effect of adding micro-alloys is to refine the grain size, control the hardenability, or aid in the precipitation process.

Figure 12 shows how increasing amounts of Columbium will reduce the size of austenitic grains at 1175° C. Current practices in the oil producing industry is to manufacture pipeline steels with levels up to 0.06% of added Columbium. From Figure 12 it can be seen that significant added grain refinement continues to occur with up to 0.15% added Columbium [27].

The steel refining processes themselves have advanced to such a degree that it is possible to reduce the levels of sulfur impurities to below 0.010%, while controlling the inclusion shapes of the remaining sulfides [46], [21].

Sulfur impacts dramatically upon the energy absorbing capabilities of a steel, decreasing the Charpy V-notch value linearly as the percent of sulfur increases (Figure 13). Research by the British Steel Corporation has demonstrated the value of alloying a steel with a rare earth element [15]; the effects of the addition of Cerium to steel can be seen in Figure 14.

The process of micro-alloying can not be done injudiciously; as long as the carbon content of the steel is kept to

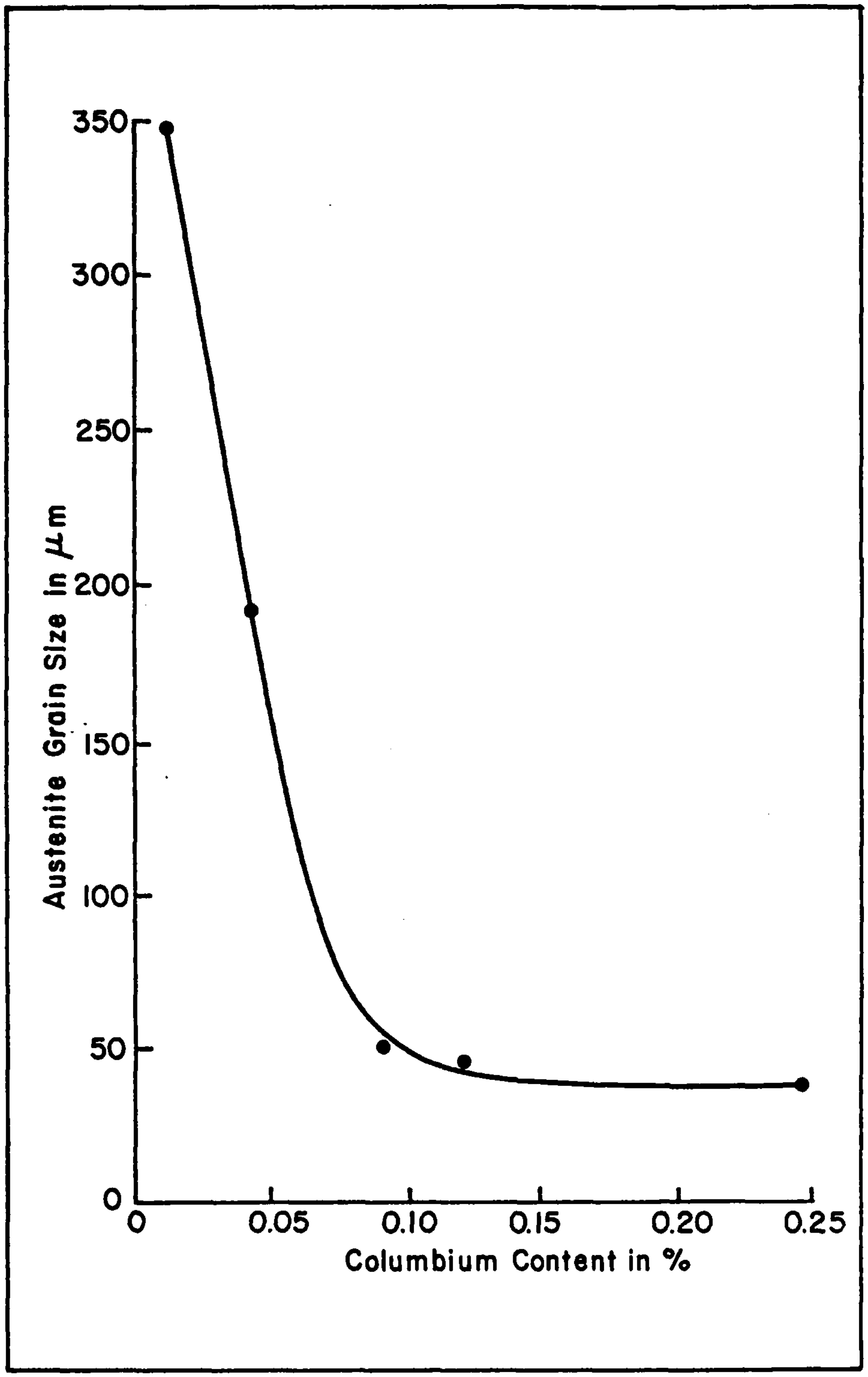


Figure 12. Effect of niobium content on austenite grain size at 1175°C soaking temperature[27]

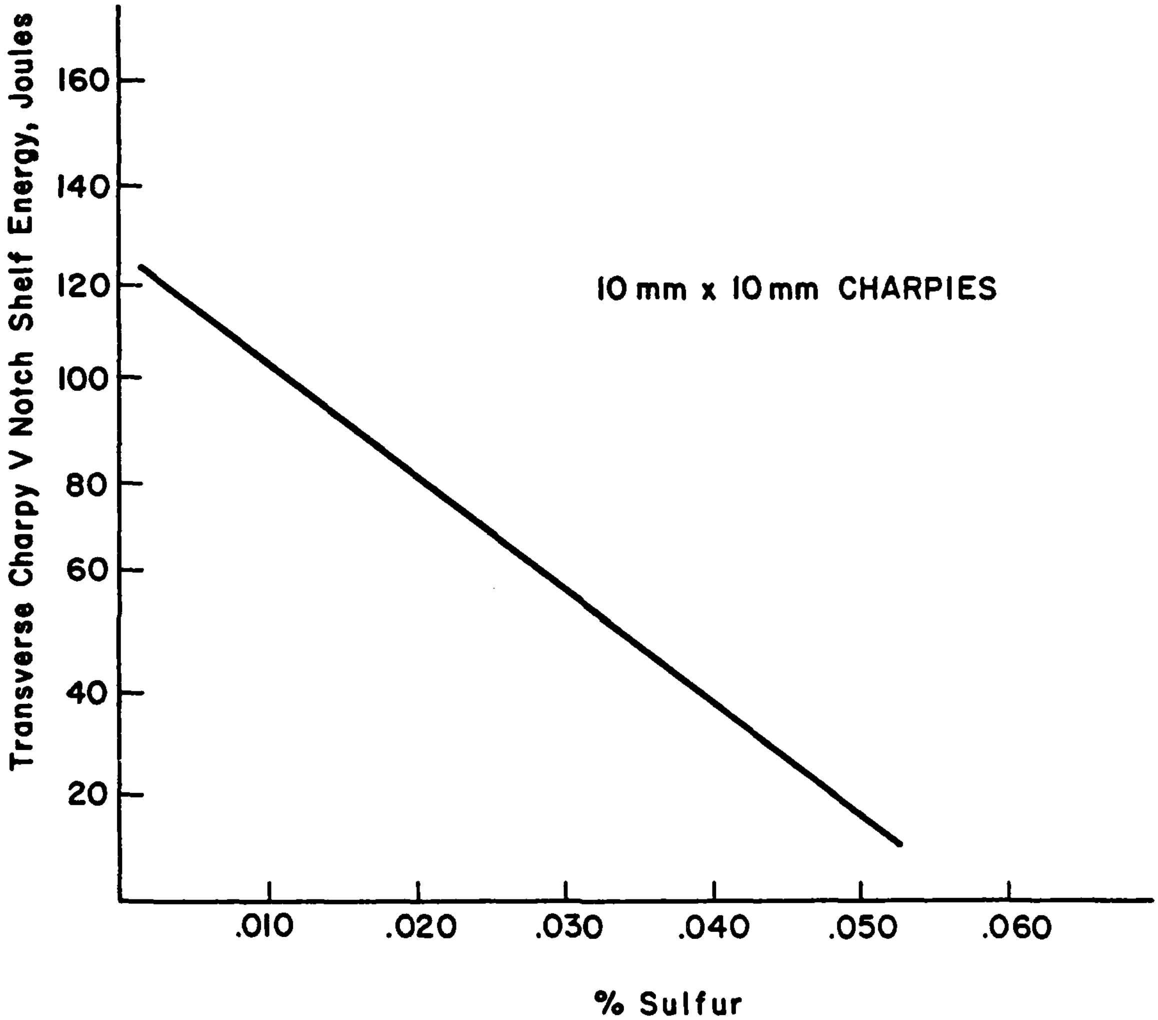


Figure 13. The effects of sulfur on the transverse shelf energy of normalized C-Mn-Nb-Al & steel plates [15]

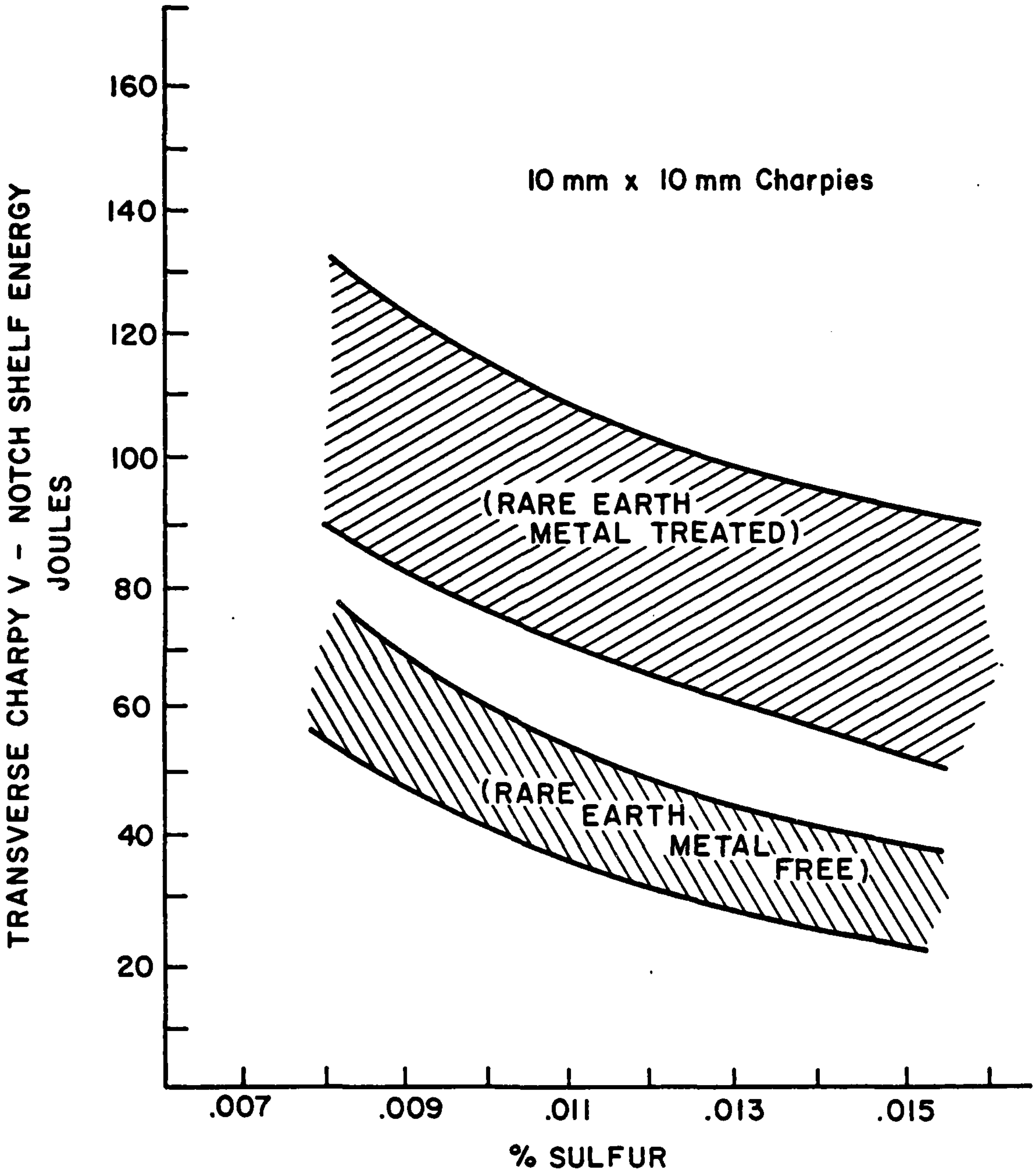


Figure 14. The effect of sulfur level and sulfide modification with a Rare Earth metal (Cerium) on the transverse Charpy V Notch shelf energy [15]

a minimum value consistent with the desired strength levels, the segregation of the added phosphorus, columbium, vanadium and/or manganese can generally be tolerated [25].

Dual-phase steels, which were heralded so loudly in the mid and late 1970's by the automotive industry, have regions throughout a ferrite microstructure containing uniformly distributed high-carbon martensite. These steels gain a significant portion of their strength through rapid work hardening, a characteristic that was not initially used to its fullest extent by automobile manufacturers [14].

Perhaps one of the most promising HSLA steels are the *Controlled rolled* steels. Unlike the manufacturing processes which use normalizing, controlled rolling is much more energy efficient; this is due to the fact that the steel is only using energy to heat it once. Figure 15 shows schematically the differences in the manufacturing processes between normalized steels and control rolled steels.

Steel that is normalized is rolled only once as it cools to the ambient temperature, which results in a transformed austenitic grain structure. The process of heating the steel to a predetermined temperature (normalizing) is used to change the steel's microstructure once again, resulting in a fine ferrite and pearlite after cooling.

Controlled rolling uses three or more rolling processes as the steel cools. Each of the rolling stages is conducted while the steel is at a specific temperature range. The end result is that the steel is given a longer period of time to

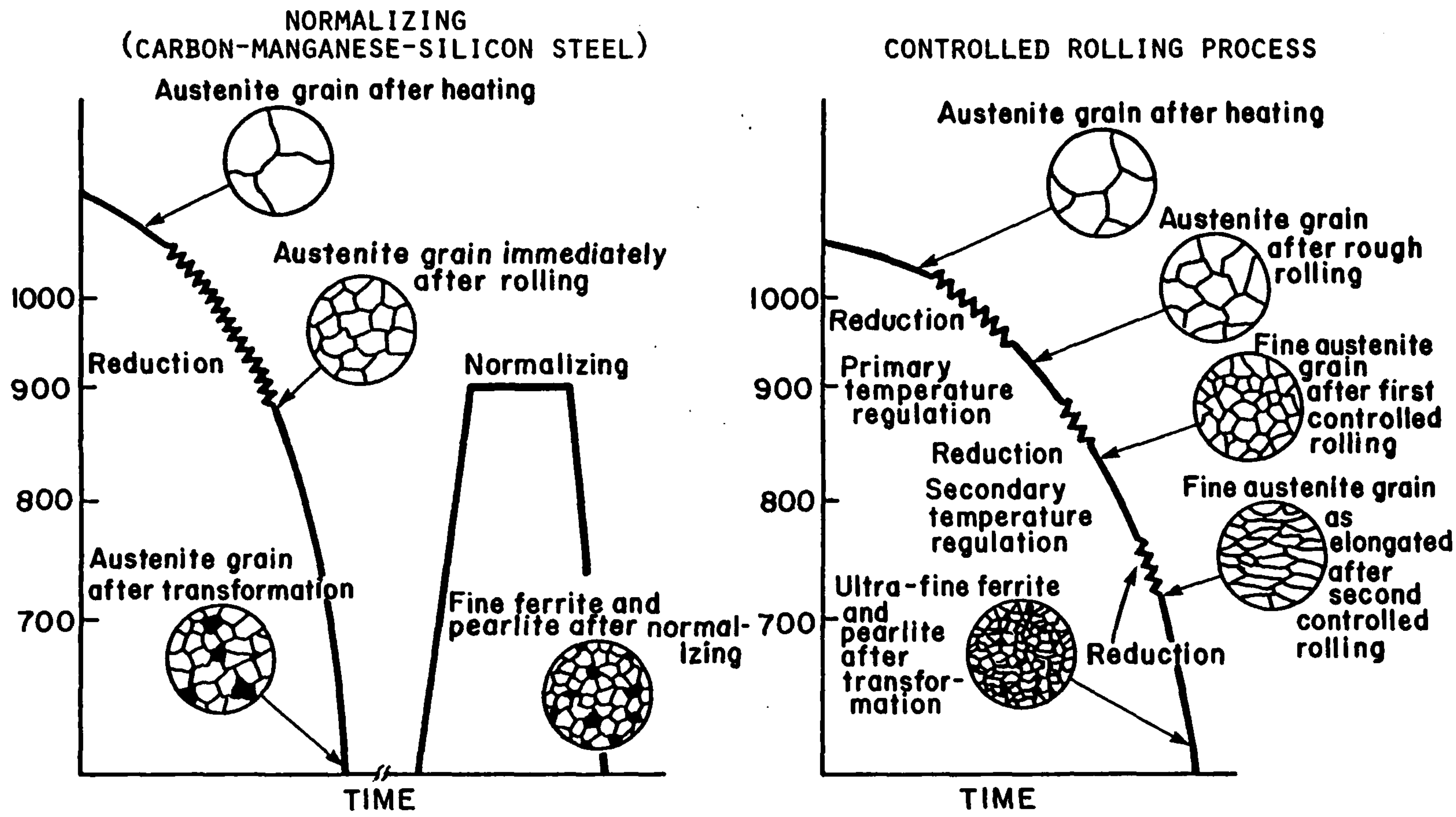


Figure 15. Schematic changes in microstructure obtained by normalizing and controlled rolling [27]

cool down to the ambient temperature, but the resulting microstructure is composed of ultrafine ferrite and pearlite.

Exclusive of weathering and quench and tempered steels, steels manufactured by the methods of controlled rolling, dual phasing, or micro-alloying are currently the most well known HSLA steels.

Two other HSLA steels are the *pearlite reduced* and *acicular ferrite* steels. The former are steels which gain their strength by a fine grain ferrite microstructure and precipitation hardening. By using very little carbon, little or no pearlite is formed, thus giving this type of steel the name *pearlite reduced*. *Acicular ferrite* steels also contain an extremely low level of carbon, but the grains form into a very fine, high strength, acicular ferrite (low carbon bainite) structure when cooled, as opposed to the more common polygonal ferrite grain structure.

Many of the HSLA steels combine two or more of the described manufacturing processes, the use of micro-alloying and controlled rolling being an example.

High strength low alloy steels have been developed from many decades of devoted research, and they are now coming into use in a variety of products, in far greater numbers than a decade ago. A problem that exists today is that not all of the decision makers in industry are aware of the new families of HSLA steels. The characteristics which have made HSLA steels so difficult to work with in the past are either no longer applicable, or they are not as pronounced as before.

This author has found in his research, engineers that are of the opinion that HSLA steels are one of the most difficult steel products to work with. This contrasts sharply with the opinion given by other engineers that "The stuff is so easy to weld with my four year-old could weld it." *

* NOTE: So as not to cause any unnecessary embarrassement, the sources of these statements will remain anonymous. They were made by representatives from private shipyards.

III. Current Practices in the United States

The research conducted for the new series of high strength steels began with a survey of the current practices in the United States. Information from governmental agencies, including the United States Navy and Coast Guard, the Office of Merchant Marine Safety, and the Interagency Ship Structure Committee was obtained; nongovernmental agencies, including the American Petroleum Institute, the American Association of State Highway and Transportation Officials (AASHTO), the American Society for Testing and Materials (ASTM), the American Welding Society (AWS), and the American Bureau of Shipping (ABS) were also consulted. Steel manufacturers and steel users were queried by a questionnaire sent directly to them with an accompanying cover letter. (See appendix A)

A total of 69 questionnaires were sent to various leaders in the steel industry. The return rate was expected to be about 33 percent. This was based upon information obtained from other researchers who have used questionnaires for conducting surveys of various industries in the past. Each questionnaire was limited to six questions. It was hoped that by placing only a few questions on the questionnaire, a greater percentage would actually be answered. This researcher was fortunate enough to have a response rate of 51 percent. After the removal of those responses that did not add constructively to this project, a final return rate of 42 percent was obtained.

The steel manufacturers and shipyards surveyed were not limited to those that had very large net earnings. This was done so that large government contractors, who typically show low net earnings, were not excluded.

The purpose of the industry survey was to determine which practices are used in the commercial sector. There are many welding processes and weld cracking tests available to academic researchers. This is because academia and many steel manufacturers are willing to experiment and develop new ideas and methods without the need for an immediate application that is both simple and economical.

Shipyards and other end product users, however, tend to use proven methods and resort to experimentation only on a relatively small scale. This is because their product is a completely erected structure, whether it is a ship, an oil storage tank, a bridge, or a building. The corporation underwriting the construction generally does not desire to get directly involved with the processes used by the steel erector. Thus the only incentive for a steel erector, such as a shipyard, to experiment or try new methods is if an immediate application to their product can be found. The interest exists at this level because it might be helpful in obtaining a larger market share or reduce the costs of assembly.

A large research and development effort is being devoted by a few shipyards that are currently building new vessels for the U.S. Navy. It is certain that these shipyards expect to profit from their endeavors. A substantial portion of the research being conducted by these shipyards is being financed by the Navy, but the shipyards will also benefit in that they will gain valuable experience using new production techniques that have an apparently interested sponsor. From the Navy's point of view, the more producers that have the capability and facilities to perform the work which they desire, the more competitive future contracts will be. It is obvious that if only one shipbuilder can construct vessels using the materials or techniques specified, then a monopoly exists, and it becomes easier for the shipbuilder to ask for *carte blanche* when tasked with a job that only they can perform. Thus, the capital the Navy now spends to sponsor research at various shipyards will eventually become a handsome investment.

The tabulation of the responses to the questionnaire indicated that the manufacturers of high strength steels in the United States generally recommend four different welding processes for their products. Those processes are: Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Gas Metal Arc Welding (GMAW), and Flux Cored Arc Welding (FCAW). The shipyards use the following processes when joining metal, in order of decreasing frequency: GMAW, SMAW, GTAW, SAW, FCAW, and Electrogas welding.

The various regulatory agencies recognize many forms of welding; including Electroslag and Electrogas,as well as all of those processes most frequently recommended by steel manufacturers.

Responses to the question about weld cracking tests did not always discuss weld cracking tests. Instead, many responses detailed fracture tests or weld quality inspection test methods. Only two corporations surveyed specifically performed weld cracking tests; the test used by the one company was the Cruciform test. A research team at a major steel producer returned the only other documented knowledge of weld cracking tests. While they did not indicate which specific tests that they used, they were familiar with an extremely long list of tests. Table 2 summarizes these tests, and their purposes.

It is important to recognize that steel mills will perform almost any test that a steel purchaser desires, if the buyer is prepared to absorb the costs for those tests. Less common tests, such as the MIT test [13] (see Chapter IV for further detail), could be performed by the contracted steel mill, but only after the procurement of the necessary equipment, which would be at the buyer's expense.

The pricing guide published by the Republic Steel Corporation for hot rolled carbon and high strength low alloy steel plates offers the purchaser the option of specifying the performance of additional tests when ordering steel. Republic Steel charges from 15 cents per hundred pounds of ordered steel (with a $50.00 minimum charge) for longitudinal impact tests, "For Information Only", to $2.35 per hundred pounds for ultrasonic inspections [47].

The new cracking tests that have been developed in both Japan and Europe, such as the Tensile Restraint Cracking (TRC)

Table 2

SUMMARY OF WELD CRACKING TESTS

Self-Restraining Tests

1.	Battelle Underbead	Cold	Cold	Bead-on plate tack weld	Ranking
2.	Lehigh Restraint	HAZ,WM	Cold,Hot	Groove	Critical Preheat Critical Slot Length (Restraint)
3.	Tekken	HAZ,WM	Cold,Hot	Groove	Critical Preheat
4.	Controlled Thermal Severity	HAZ	Cold	Fillet	Thermal Severity Number, (Critical) Thickness)
5.	Cruciform	HAZ	Cold	Fillet	Ranking
6.	Circular Patch	HAZ,WM	Cold,Hot	Groove	Ranking, Critical Patch Diameter
7.	Gapped Bead-on Plate	WM	Cold	Bead-on-Plate	Ranking, Longitudinal Stress
8.	Schnadt-Fisco	HAZ	Cold	Groove, line-pipe girth	Critical Travel speed, (Energy Input)
9.	Welding Institute Restrained Butt-weld	HAZ	Cold	Groove, Line-pipe girth	Critical Energy Input, Critical Preheat
10.	Slot Weld	HAZ	Cold	Bead-on-groove, line-pipe girth	Critical Preheat, Critical Time
11.	Rigid Restraint	HAZ,WM	Cold	Groove	Critical Transverse Stress
12.	Welding Institute of Canada	HAZ,WM	Cold	Groove	Critical Preheat Critical Fillet Size (Restraint)

Externally Loaded Tests

1.	Murex	WM	Hot	None	Ranking, Crack Length
2.	Varestraint	WM,HAZ	Hot	None	Critical Strain, Crack Length
3.	Tensile Restraint	HAZ,WM	Cold	Groove	Critical Transverse Stress
4.	Implant	HAZ	Cold	None	Critical Stress
5.	Augmented Strain	HAZ,WM	Cold	None	Critical Stress, Basic Mechanisms

test, are not universally known by all survey participants, although many monitor new test methods as they are developed. There exist groups within many of the steel manufacturers that devote time to researching and writing reports for outside contractors; these groups tend to be the personnel that are most familiar with the various tests performed around the world.

Those shipyards that would be interested in using new tests conditioned their response with statements of "economic value", the ability of the tests to duplicate "production" techniques, and the "acceptance" by various regulatory agencies. Those agencies specifically mentioned included the American Bureau of Shipping, Lloyds, the United States Navy and Coast Guard.

Many nongovernmental agencies detail specific weld cracking tests, and how they should be performed. Typically these tests are used to qualify new procedures, materials or production methods. The methods used by the American Bureau of Shipping (ABS) are the Reduced Section Tension test, and the Root Bend, Side Bend and Face Bend tests [2]. In addition to these tests, both the American Welding Society and American Society for Testing and Materials also use the Varestraint test and the T-bend tests [11], [10]. The American Association of State Highway and Transportation Officials uses the Longitudinal Bead Weld Underbead Cracking Test [1]. Numerous other tests exist which measure the ability of a welder to make quality welds. Some of these are capable of detecting larger cracks. The hydraulic testing of a piping section is an example of this.

Steel *Manufacturer B* publishes a small book detailing their suggestions for welding high strength steels. The book comes complete with a photograph of an underbead weld crack, and a list of four precautions to follow in order to reduce moisture pickup in low hydrogen electrodes. Every one of the precautions listed by this manufacturer are more stringent than those suggested by electrode manufacturers. Another section of the book is dedicated to the reduction of entrained moisture in welding fluxes. Appendix B details the precautions that steel *Manufacturer B* suggests.

Steel manufacturers usually recommend welding processes and electrode combinations for use with their product, and suggest very generalized methods for the control of weld cracks. The use of increasing preheat as the thickness of the plate to be welded increases is universally recommended. Many steel manufacturers recommend that a welding supply manufacturer be consulted for detailed methods for the control and prevention of weld cracking. One surveyed welding supply manufacturer makes the following recommendation:

> Low hydrogen coated electrodes shipped in nonhermetically sealed containers should be placed in a drying cabinet at a minimum temperature of 400° F for 24 hours prior to being used if optimum procedure is followed. However, it is realized that fabricators utilizing low hydrogen types usually use the electrode directly from

the container [53].

This particular company recognizes that the practice of using the electrodes directly out of the shipping container does occur, and while it stresses the need to use a drying cabinet to ensure against unwanted moisture pickup, they also use a high moisture resistant, low hydrogen coating for their electrodes. Their recommendations continue:

> Low hydrogen electrodes received in hermetically sealed containers may be used directly from the container, but after the container is open there are necessary precautions to be taken against moisture pickup. If the electrodes are exposed for hours in high humidity or for approximately 8 hours in low humidity, these electrodes should be reconditioned for 4 hours at 400° F temperature in a drying oven. The precaution of excessively high temperatures is also necessary with low hydrogen coatings due to premature disassociation or chemical reaction of certain coating compounds. Therefore, it is important that the 400° F temperature be adhered to [53].

Most users responding indicated that they used some form of welding material moisture control. Appendix B gives further detail into the methods used by the various shipyards to control and prevent weld cracking.

The second most prevalent form of controlling weld cracking was preheating; this was recommended always when the possibility of the metal surfaces being damp existed. All of the regulatory agencies and major construction codes specifically address the subject of preheating the workpieces when the ambient temperature drops below the range of 0 - 32° F. This is usually done to remove surface moisture not readily visible to the naked eye, and to compensate slightly for the anticipated decrease in weld quality resulting from welder discomfort [1], [2], [9].

The requirements for preheating various plating grades and thicknesses can be found in the appropriate regulatory or classification society rules. Some of these can be very detailed, and require that a minimum temperature be obtained under a variety of different conditions. Those conditions include the base plate tensile strength level, thickness at the joint, and carbon content [2].

Since there are many situations that would not be covered specifically by agency rules, or could be affected dramatically by the introduction of a new type of steel, this researcher investigated the clause "The preheating of other materials will be subject to special consideration" found in the ABS rules [2].

For most new procedures it is not difficult to obtain approval by the certifying agency on a case basis. A variance must be applied for, and upon review it is either accepted or rejected. This procedure must be repeated for each application, and it generates another piece of paperwork. When a new material enters upon the scene and makes certain rules overly restrictive, the rules can be changed. The process of changing the rules requires the meeting of the respective Rules Committee, which occurs on a regularly repeating basis. It is important to realize that the rules are meant to be general, and the procedure for changing them is not intended to be arduous [60].

Four different formulas for the calculation of the carbon equivalence were returned in the questionnaires. Many shipyards do not address the subject, or only limit the percent of carbon alone, while the steel manufacturers are willing to use almost any formula that a potential buyer suggests. The fact that many shipyards do not concern themselves with carbon equivalence formulas should not be detrimental to the work they perform since most shipyards do not design the products which they build.

Most regulatory agencies do not have a carbon equivalence formula for high strength steels, but they might impose requirements for certain specific practices.

Appendix A contains sample copies of the questionnaires and cover letters sent to the steel manufacturers and shipyards.

Appendix B summarizes the responses to the questionnaires, the reader is urged to consult it for additional detail.

Appendix C presents the specific carbon equivalence formulas used by the respondents to the questionnaire.

IV. EXPERIMENTATION

THE STEELS EXAMINED

The high strength low alloy (HSLA) steel being evaluated is K-TEN80CF, a product of Kobe Steel, Ltd. from Kahogawa-city, Japan. The two types of steel against which it is being compared, are T-1b and HY-80. These steels were chosen in order to compare the K-TEN80CF against high strength steels commonly used in the United States. All three steels are micro-alloyed and quenched and tempered.

Kobe Steel, Ltd. supplied three plates 25.4 mm thick (one inch stock), measuring 1100 mm (43.3 inches) by 1600 mm (63 inches), along with a supply of welding electrodes. The plates were rough cut to the sizes required for the tests using an oxyacetylene cutting torch. The welding electrodes sent by Kobe Steel, Ltd. were: L-118 stick electrodes (AWS classification E-11018M) in a 4.0 mm diameter, and two spools of MGS-80 gas metal arc (GMA) welding wire in a 1.2 mm size. Both the welding wire and stick electrodes have a tensile stress classification of 80 kgf/mm^2.

The T-1b and HY-80 steels were also obtained in a one inch thickness, but they were received ready to mill, not needing any further rough cutting.

T-1b has a yield strength of 100 KSI, while HY-80 has a yield strength of 80 KSI. The K-TEN80CF is classified as having an yield strength of 70 kgf/mm^2 (99.5 KSI). The manner in which steel is classified in Japan, along with the conversion from metric to imperial units of measure, make it difficult to get steels with identical strength properties.

For the purposes of comparison, Table 3 lists how the chemical compositions of the steels differ. With the exception of the K-TEN80CF and T-1a, this information was obtained from manufacturer's data rather than a ladle analysis. The specific ladle analysis for the HY-80 was not available. In order to help the reader compare these chemical compositions to other steels, three additional steels not included in the testing program have been included in Table 3: HY-130 (Yield strength of 130 KSI), a high strength low alloy steel alloy alloy steel manufactured in the United States (HSLA-80, yield strength of 80 KSI), and a low carbon steel.

TESTING PROGRAM

The evaluation of the steel's susceptibility to weld cracking was to be examined by the usage of the Tekken (Also known as Y-Groove), the Lehigh, and MIT tests. The first two tests are widely known and used tests, and were developed in the United States in the mid 1940's and in Japan in the mid 1950's respectively [50], [51], [42]. "Tekken" is an abreviation for *Tetsudo-Gijutsu Kenkyusho*, which is Japanese for the Railway Technical Research Institute, Japanese National Railways, while the Lehigh test obtains its name from the university where most of the developmental work performed. The MIT test was the result of work performed at Massachusetts Institute of Technology by J. Biederka in 1983 [13], hence its

Table 3 - Composition of Steels by Weight Percent

Alloy	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Cb	V	Al	B	Ti
K-TEN80CF	0.07	1.06	0.010	0.003	0.24	0.41	1.01	0.39	0.24		0.046		9×10^{-6}	
T - 1a	0.18	0.88	0.013	0.013	0.25	0.57		0.21			0.055		0.0012	0.021
HY - 80	0.18 max	0.1-0.4	0.025 max	0.025 max	0.15 0.35	1.00-1.80	2.00-3.25	0.20-0.60	0.26 max		0.03 max			
HY - 130	0.16	0.6-0.9	0.015	0.015	0.15-0.35	0.40 0.70	4.75 5.25	0.30-0.65	0.20 max		0.05 0.10			
HSLA - 80	0.07 max	0.40-0.70	0.025 max	0.010 max	0.40 max	0.60-0.90	0.70-1.00	0.15-0.25	1.00-1.30	0.02 min				
Low Carbon	0.06	1.9	0.010	0.005	0.15			0.35		0.03		0.03		

name.

The Tekken test has been developed in two forms, the "standard" test sample measures 330 mm (13.0 inches) by 150 mm (5.9 inches) while the "modified" sample measures only 200 mm (7.9 inches) by 150 mm (See Figure 16). The restraint for these tests is obtained by the welding together of the two initially separate pieces.

Research done by H. Hoikawa *et al.* [28] has found that the restraint applied to a modified Tekken test can be calculated using the equation,

$$K = K_o \times h.$$

When the thickness of the plate, h is expressed in millimeters, and when K_o, the restraint intensity coefficient, is expressed in Kg/mm^2/mm, the total restraint of the plate is found in terms of Kg/mm/mm. Figure 17 illustrates the effects of varying the length of the test specimen, and the width of the gap forming the "leg" of the "Y" groove.

For a test plate measuring 200 mm, with a gap size of 2 mm, the value of K_o can be found from Figure 17 to be approximately 141 Kg/mm^2/mm. Thus, for a plate thickness of 25.4 mm, the total restraint applied to each specimen before the application of the weld to be tested, is approximately 3581 Kg/mm/mm.

Assuming that all other variables such as welding speed and voltage remain constant, it can be expected that the variance in the restraints actually found in each test sample would be caused by:

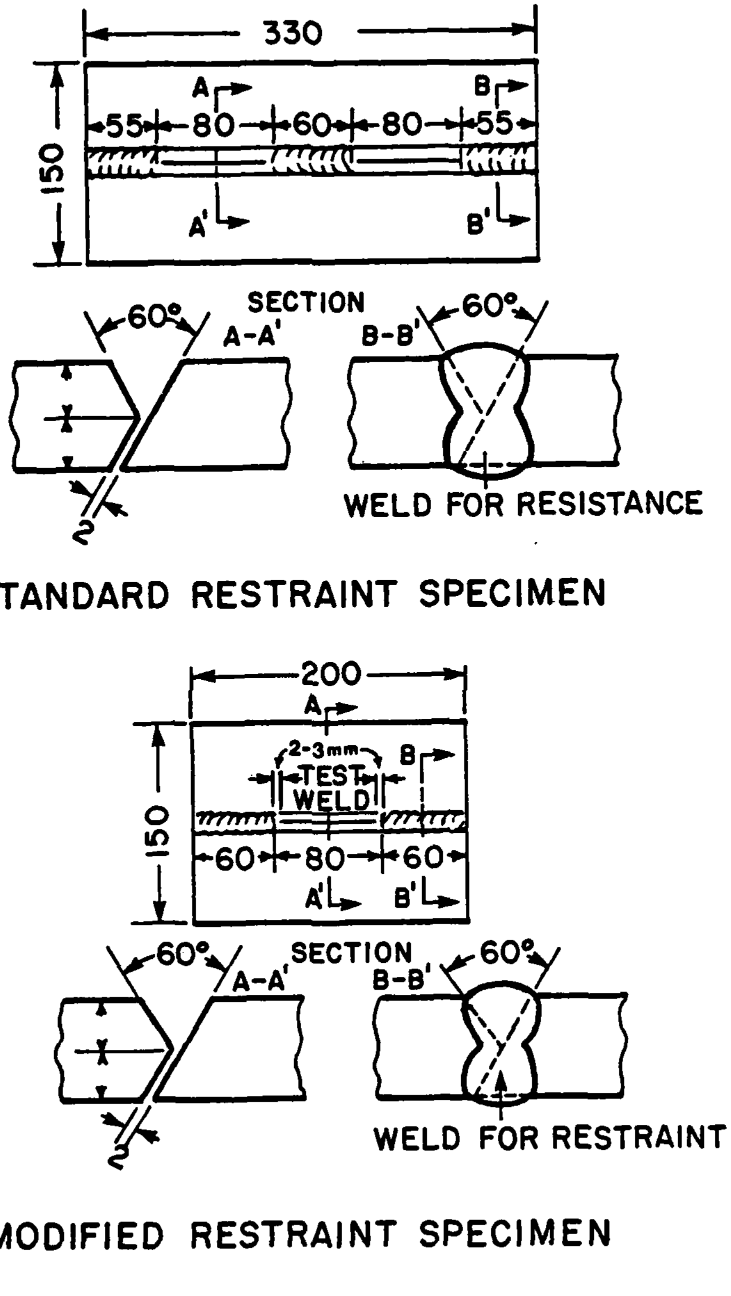


Figure 16. Tekken restraint cracking specimens (standard and modified) [36]

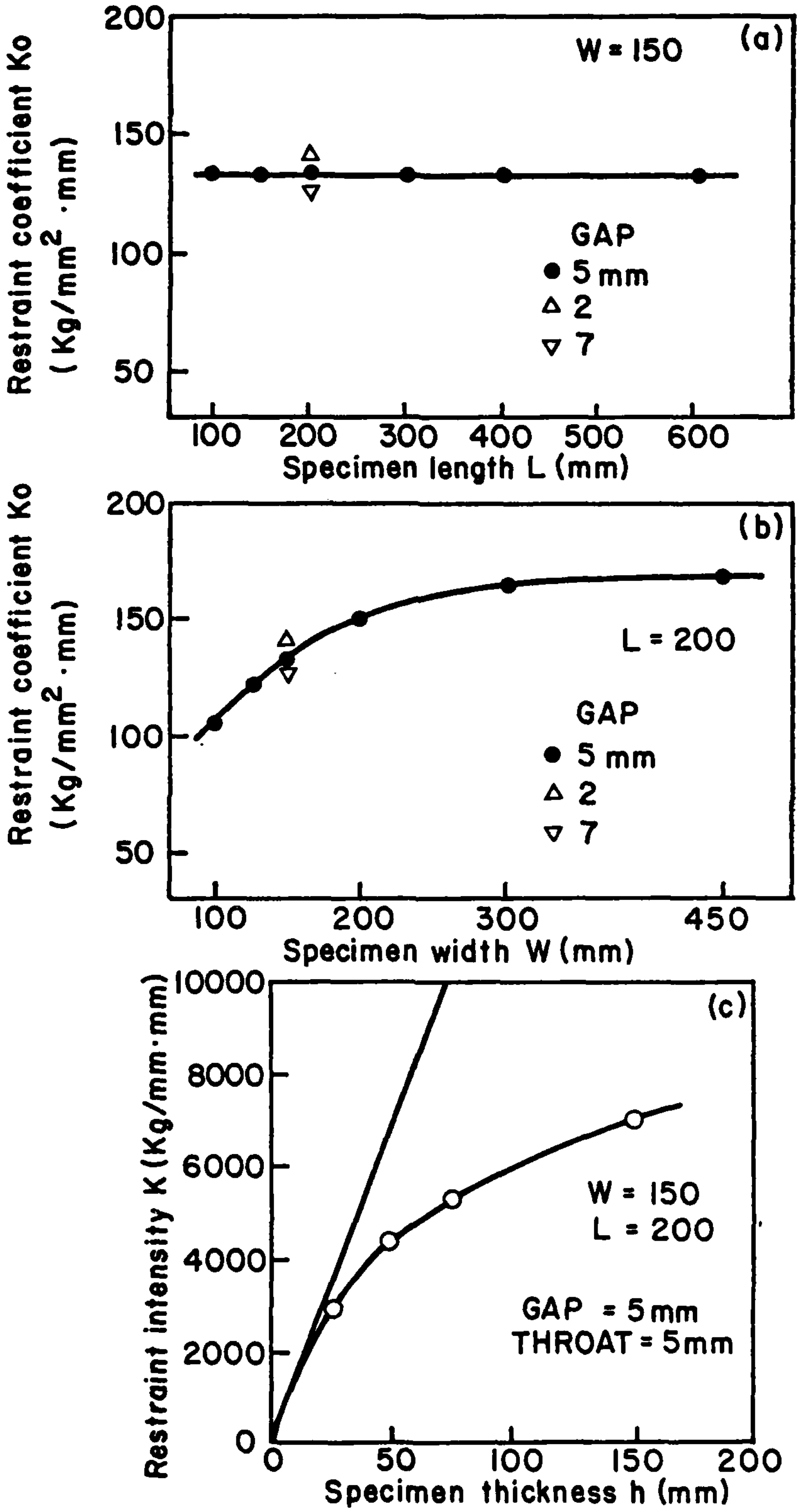


Figure 17. Numerical calculation of restraint coefficient and restraint intensity [28]

(1) The extent of the penetration of the joining welds along their length,

(2) The amount of heat input into each restraining weld, (which is a function of the distance from the work-piece to the gas cup),

(3) The cooling rate of the steel.

For the purposes of these experiments, the actual restraint for each plate will be considered to be constant. While this is artificial, it is a totally random process, and should impact equally upon all three types of steels.

The Lehigh test uses a plate that measures 12 inches (304.8 mm) by 8 inches (203.2 mm). Two 1/2 inch (12.7 mm) holes are drilled along a centerline placed parallel to the 12 inch side. The holes are joined by a milled cut that is detailed in Figure 18. The "land" between the milled cuts is omitted if the specimen size is less than 3/4 of an inch (19 mm). For plates that are greater than or equal to one inch in thickness, the centers of the holes are separated by 5.5 inches (139.7 mm); for those plates which are less than one inch in thickness the holes are only 3.5 inches (88.9 mm) apart.

Restraint of a Lehigh test sample is obtained by the addition of slits placed along the edges of the plate as shown in Figure 18. The greatest amount of restraint is obtained when the slits are not added. The amount of restraint found in a Lehigh test sample is expressed numerically as the

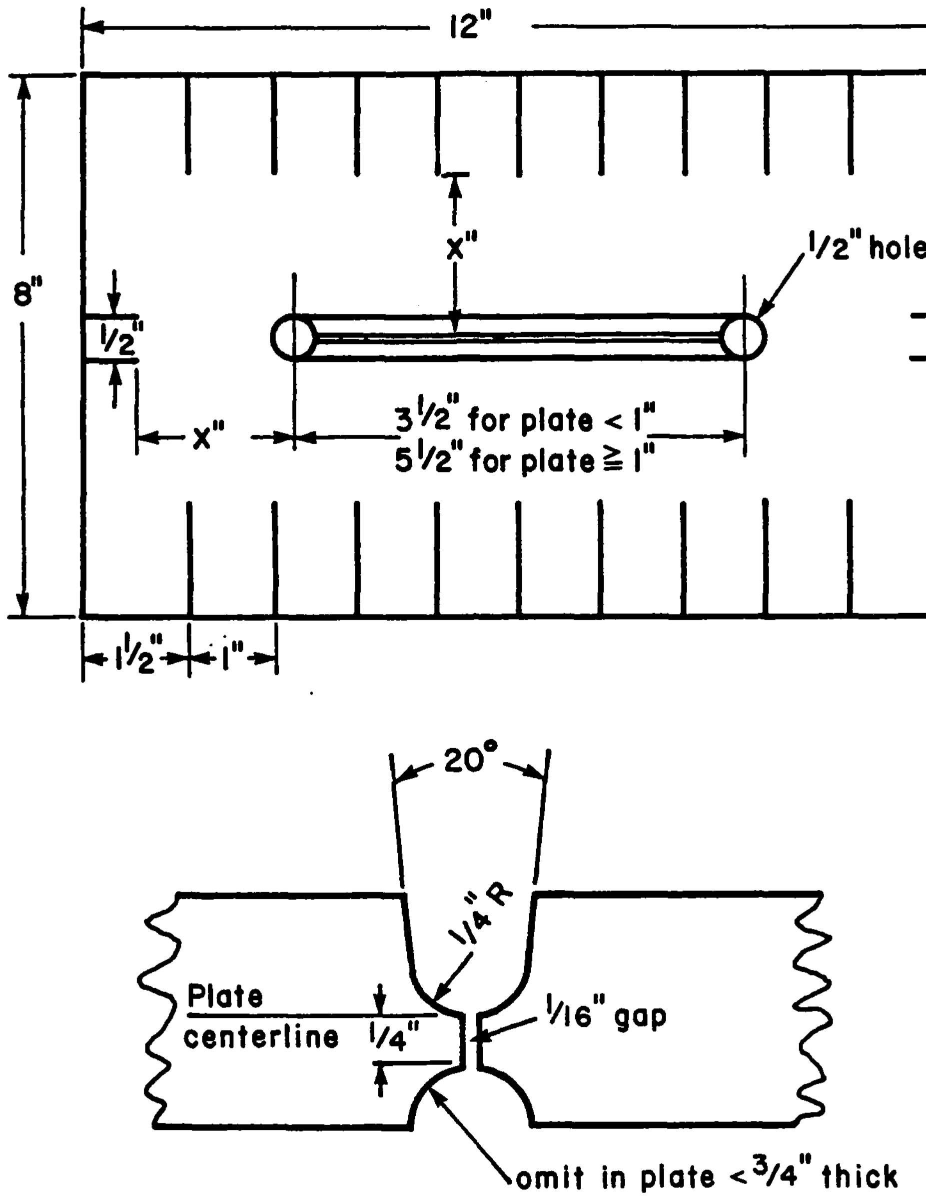


Figure 18. Lehigh restraint cracking specimen [50]

distance between the inner ends of the edge slits, or by the length of the slits themselves. An immediately apparent advantage of the Lehigh test is the fact that the restraint will not depend upon a possibly variable welding procedure.

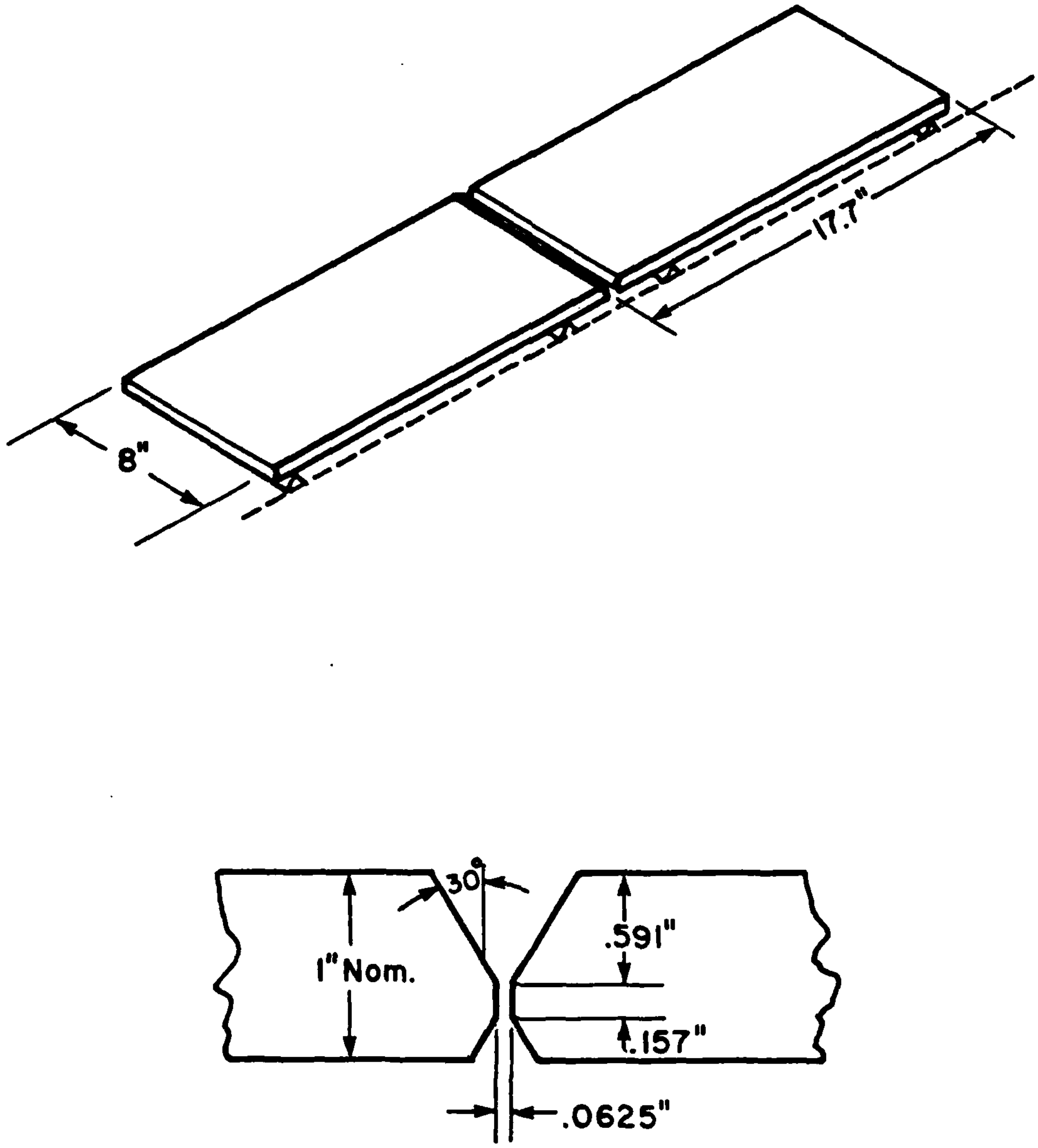
Both the Tekken and Lehigh tests have a disadvantage in that they are of the "go" "no-go" form. In other words, if the test sample does not crack, very little is learned. However, if the test plate does crack, all that is learned is that less restraint is required for the plate not to crack.

The MIT test on the other hand is an applied restraint test, thus a definite cracking point can be discovered with each test specimen.

The MIT test uses two plates that measure 17.7 inches (449.6 mm) by 8 inches (203.2 mm). The plates are joined when the test is actually being conducted as found in Figure 19. The initial restraint can be varied by the placement of the restraining welds along the edge of the plate. These welds join the test plate to the restraining fixture. (See Figure 20) typical restraining weld lengths are 5.5 inches (139.7 mm) long.

The intensity of restraint developed by the MIT test can be approximated by an equation developed by J. Biederka, since these tests are not completed as of this writing; the equation will not be repeated here. The reader is referred to the work of J. Biederka for further information [13].

Due to delays in the testing process beyond the control of this investigator, it was impossible to perform all three



Detail of weld joint preparation

Figure 19. MIT restraint cracking test [13]

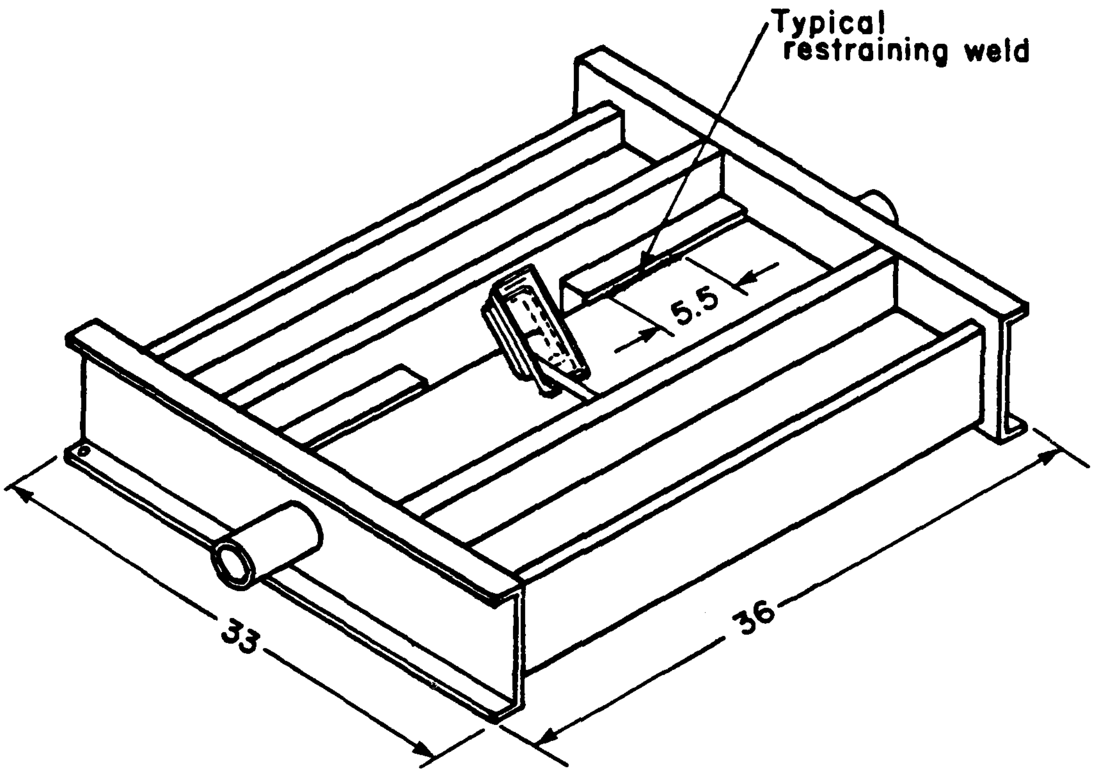


Figure 20. Test set up for MIT restraint cracking test[13]

tests before the final preparation of this document. Therefore, this investigator will report upon the results of the Tekken tests.

The Lehigh test is known to be more sensitive to the cracking due to the electrode, while the Tekken test is better suited for the testing of the parent metal [36]. The fact that the Lehigh test is better known in the United States, and the Tekken test is widely used in Japan, also contributed to the process of selecting weld cracking tests.

The fact that the Lehigh and Tekken tests are self-restraining also counted favorably in their ultimate selection. Tests which are not self restraining tend to be extremely labor intensive, requiring lengthy setup times which reduce the number of tests which can be performed in a given time frame.

PROCEDURE

All of the Tekken test specimens used for this report were welded using Gas Metal Arc Welding (GMA), direct current reverse polarity (dcrp). Using dcrp is more common than using direct current straight polarity (dcsp) when GMA welding, and it yields a deeper weld penetration than dcsp. For the GMA welding process, a shielding gas of 80% CO_2 and 20% Ar was purchased. This mixture of gas was recommended by Kobe Steel, Ltd. for use when welding with the MGS-80 wire. Initially the experimentation was to have been accomplished using this shielding gas, combined with the MGS-80 electrode wire for all three types of steels, and while it was used to join the ends of the Tekken test samples, this procedure was thought not to be fair to the T-1a and HY-80, and was therefore modified. The ends of the samples are not a part of the area used to obtain data for the test results, and welding the ends of each test plate with the materials supplied by Kobe Steel was not thought to adversely affect the testing.

From a scientific standpoint, it is easier to identify the cause of cracking if only one parameter is changed with each of the different steels, leaving the other items as the control. The problem with attacking the problem with this approach is that each steel has a different set of ideal conditions and consumables that should be used together as a complete package. In an effort to fairly assess the cracking resistance of the three steels, it was decided to forego the simplicity of a single variable (the steel), and create the welds to be tested using the optimum set of conditions. As a result of this decision, the shielding gas used for the welding of the T-1a and the HY-80 was 98% Ar and 2% O_2.

The welding wire used for the HY-80 and T-1a test welds was also changed to Airco AX-90 type 100S-1, which meets military specification MIL-E-23765/2.

The gas cup used for all of the GMA welding was 0.875 inches in diameter, and the distance from the bottom of the gas cup to the test pieces was set at approximately 1/2 inch for each experiment. Since this distance was approximate, it would be expected that the welding current used would vary slightly from experiment to experiment. This can be seen in the tables found in Appendix D that tabulate the welding parameters used for each test.

The welding parameters finally chosen were the result of a number of trial welds. From a materials standpoint, it was unfortunate that many trial welds were required before a method for welding each of the steels could be perfected.

In order to conserve steel, and because the "standard" Tekken test actually contains two test welds rather than one, the "modified" version of the test was used. The steel shapes were rough cut to size by flame cutting, but in order to remove any area that might be flame hardened in the region to be welded, the final preparation of the steel was performed by milling.

Each Tekken test sample was joined by the use of multiple welding passes on the top surface where a large volume of welding materials needed to be deposited, and a single pass on the bottom side. In order not to initiate any weld cracks during the preparation of the Tekken samples, each plate was preheated to a minimum of 150° C before joining the two halves, and after being welding they were allowed to cool slowly back to room temperature by placing them into the preheating oven, which had since been turned off.

It was discovered that the Tekken test plates could not merely be joined together, because when the weld puddle came to the edge of the plate, it would run off the steel, creating a depression in the filler metal deposited in the "Y" groove

(See Figure 21). In order to overcome this minor obstacle, welding runoff tabs were placed at the trailing edge of each restraining weld. So as not to alter the amount of restraint between test pieces, the runoff tabs were latter cut off of the plates with a *Duoall* saw.

The sequence of performing the test welds was determined as a matter of practicality. All of the K-TEN80CF plates were welded sequentially, then the HY-80 and T-1a plates were welded. This was done in order to reduce the number of times that the welding electrode wire and shielding gas needed to be changed.

In order to determine where cracking would form, and where it would not form, the test welds for the three types of steel were initially performed with preheats of 50° C (122° F), 100° C (212° F), and 150° C (302° F). This was done in order to "bracket" the critical preheating temperature, below which delayed cracking would occur.

The steels were heated to the proper temperature in an oven, where the air and steel temperatures were monitored. The steel temperature was checked by the use of *Tempil* sticks. In order to obtain the predetermined preheat temperature, *Tempil* sticks with melting points just above and below the desired preheat temperature were used to monitor the steel temperature. The repetitive opening of the oven door to check the steel temperature had the affect of driving the inside air temperature down, giving the unwary experimenter a false impression of where the steel temperature might actually be.

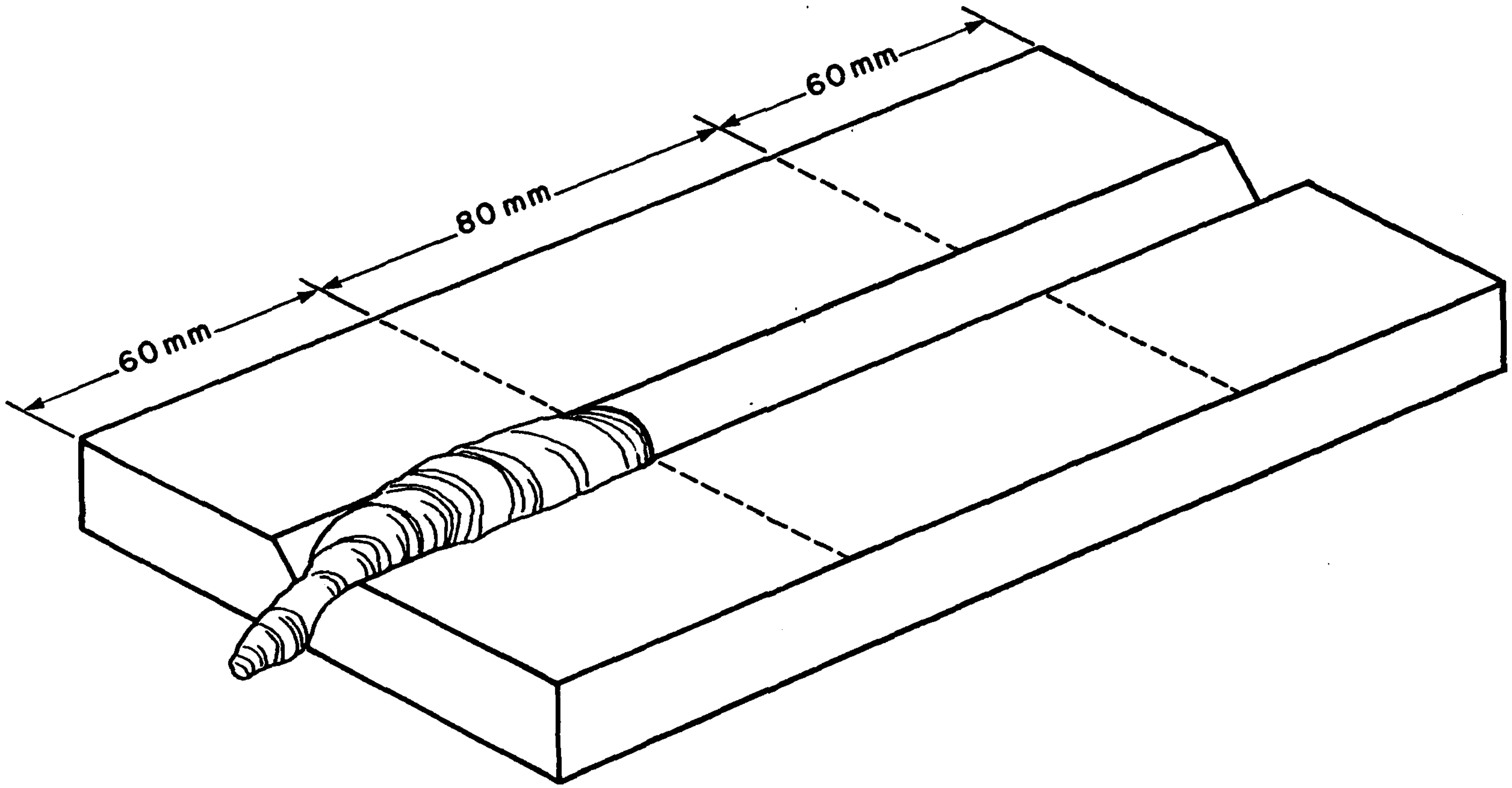


Figure 21. Tekken test specimen pieces when joined without runoff tabs

The placement of the steel within the oven was also important, as those pieces that were closer to the heating element were heated faster. This "feature" of the preheating oven was appropriately noted, and the steel temperatures were monitored more diligently.

Once the test weld had been deposited, the steel was placed on an improvised cooling rack. The HY-80 and T-1a when cooling gave off many high pitch pinging sounds. The pinging sound became less frequent as the plates cooled to room temperature. This phenomena was noticeable absent from the K-TEN80CF as it cooled to room temperature. After the first three plates from the three different steels and preheat temperatures had cooled, they were examined for cracking.

The results from the first three preheats indicated that the K-TEN80CF test plates could perhaps tolerate even less preheat than 50° C. A final set of test welds were made without the use of any preheat at 19° C (66° F).

The results and testing procedures are extensively documented and detailed in Appendix D, and will not be presented here. Rather the results will be presented.

RESULTS

All of the welds appeared to have shallow penetration; but if a weld is sound, the amount of penetration does not impact upon the quality of the joint. By increasing the heat input for the welding cycles it would have been possible to obtain deeper weld penetrations, but the welds made for the tests were all made using heat inputs close to the recommended maximum values. Occasional minor flaws were detected in the welds; however, none were judged to be serious. The welding process used to join the K-TEN80CF produced more fumes and smoke than the welding process used for the HY-80 and T-1.

Subjecting the test plates to a series of different examinations discovered which methods were the quickest, the most reliable and the least expensive. X-ray examinations could yield a significant amount of information; and when cracking was discovered using X-rays, it usually gave rapid and accurate indications to the extent of cracking. But X-rays did not always correctly determine whether cracking had occurred. The dye penetrant test was the least expensive test method, but it did not yield directly useable results. Indirectly the dye penetrant test aided in the macroscopic search for cracks, this was because it would leak out of a cross section which contained a crack. This "feature" of the dye penetrant test also occurred when a cross section was examined microscopically, but here it did not aid the search for cracking. Instead, the dye penetrant would leach out of the crack as the steel was being etched, leaving a residue that inhibited the microscopic examination. The most cost effect method for searching for cracking was the macroscopic search. Although this method could not accurately determine the extent of cracking, as an X-ray examination could, it was extremely accurate relative to the cost and labor involved. Less cost effective was the microscopic examinations, but they were 100 percent accurate in the examined region. This is because when magnified up to 1250 times, even the smallest crack appears to be very large, and can not avoid detection. A drawback to this examination method is the length of time and labor required to mount and polish each specimen to be examined.

It is this author's opinion that the macroscopic and microscopic examinations were the most useful and cost effective methods for determining which test plates had cracked. Although cross sectioning a test plate will not give precise crack lengths, the use of multiple cross sections, as was performed on test plates K1 and K4, will give indications to the approximate extent of cracking. Another advantage of cross sectioning the steel is that unlike X-ray examinations and dye penetrant tests, the results are not dependent upon the interpretive skills of an X-ray or penetrant test reader.

Table 4 summarizes the examination methods used and their individual conclusions regarding whether or not the sample had cracked. The tests are listed in the order of information obtained, and read from left to right. When the results of two consecutive tests do not agree, the test which follows was thought to be more accurate. Not all examination methods were used on each test plate, those plates that did not have a particular test performed are marked with dashes.

As a result of the examination procedures detailed in Appendix D, the K-TEN80CF steel was determined to have the highest resistance to delayed cracking. The HY-80 steel was found to be less tolerant of reduced preheating than the

Plate	Dye Penetrant	X-ray	Macroscopic	Microscopic
H7	Not	Cracked	Possibly	Not
H4	Not	Cracked	Cracked	---
H5	Not	Probably	Possibly	Not
H3	Not	Not	Not	---
K1	Not	Not	Cracked	Cracked
K4	Not	---	Not	Not
K2	Not	Not	Not	---
K3	Not	Not	Possibly	Not
T11	Not	Cracked	Cracked	---
T6	Not	Cracked	Cracked	Cracked
T7	Not	Not	Not	---
T5	Not	Not	Not	---

Table 4. Examination methods and information obtained pertaining to the cracking of the Tekken test plates.

K-TEN80CF, but more so than the T-1a. Table 5 summarizes the preheat temperatures and the whether or not the various steels cracked.

Preheat (°C)	HY-80	K-TEN80CF	T-1a
19 (None)	No cracking	No cracking	* Cracked *
50	* Cracked *	No cracking	* Cracked *
100	No cracking	No cracking	No cracking
150	No cracking	No cracking	No cracking

Table 5. Summary of Tekken test results.

The HSLA steel exhibited a superior resistance to cracking, a result which could have significant impacts upon the steel industries both here in the United States, and overseas. It is the opinion of this author that additional testing is needed in order to validate these results. That is because the results generated for this work are based only on the data gathered from one or two plates tested for each steel and preheat temperature. A statistically valid survey would require many plates of each steel to be tested at each preheat temperature; however, under the circumstances the greatest amount of information was gathered in an unbiased manner using the limited number of sample plates available.

V. IMPACTS OF HIGH STRENGTH LOW ALLOY STEELS

High Strength Low Alloy (HSLA) steels are already being used by many manufacturers, and they can be found in items as common as the family automobile, or exotic as space exploration components. In order to properly evaluate the possible impacts of a new HSLA steel upon the consuming public, it is first necessary to determine what share of the current steel market is devoted to HSLA steels.

DOMESTIC STEEL PRODUCTION AND CONSUMPTION

The steel consumed in the United States is a combination of domestic and imported products. In 1982, the last year for which this data was available, the United States imported 16.5 million (short) tons of steel products. It produced an additional 72.9 million tons of crude steel, 2.1 million tons of which it exported as finished steel products, such as castings, sheets, plates and ingots [57]. Thus the total steel consumption in the United States in 1982 was 87.3 million (short) tons.

For all of the steel which the United States did produce, it had a capacity to manufacture an additional 81.1 million tons. As a function of the total world production, the United States produced only 10.3 percent of the raw steel in 1982, when its proportional market share should have been 14.4 percent [58]. The above statistics are not extremely optimistic, and, based upon projections made by the the United States

Department of the Interior, the trend will continue. By 1985 it is projected that the United States steel producing capacity will decrease an additional 9.1 percent, while the overall world production capacity will only decease 1.5 percent. Using today's definition of the "third world", only the third world and the European Economic Community will suffer greater declines in their respective steel producing industries [58].

All of the statistics were generated during the economic "recession" that the United States was suffering in the early 1980's. Short term statistics can be unduly influenced by recent fluctuations and phenomenons. As can be seen by Table 6, 1982 was the first year in over a decade that the United States produced less than 100 million tons of total raw steel products. Nevertheless the total world demand for raw steel remained within a band of 128.4 million tons per year for the same time frame. The immediate implications of these more relevant figures is that the production of steel and its associated products in the United States is suffering from a period of economic stagnation.

	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
U.S.	133	151	146	117	128	125	137	136	112	121	73
World	693	769	780	710	742	742	788	821	787	777	707

Table 6. United States and world iron and steel production in millions of short tons.

Using figures developed by the American Iron and Steel Institute, during the first three quarters of 1983 as compared to 1982 domestic steel shipments in the United States have increased by 6.3 percent [4], [5]. The greatest increases have occurred in the areas of automotive and appliance production (such as refrigerators, cooking utensils, etc.).

The statistics for total and raw steel production in the United States are very similar to those for domestic shipments of steel plates. From 1960 through 1977 there was a generally increasing demand for steel plates, but after 1977 the requirement for steel plates dropped significantly. In a category of its own, high strength low alloy steels have suffered similarly, but the decline did not appear until 1980. More important is the fact that the only type of domestic steel demonstrating steady long term growth has been the HSLA steels. As a result, several foreign and domestic steel producers have seriously considered investing in new HSLA steel manufacturing equipment.

When energy costs were skyrocketing ten years ago, there was a flurry of activity to develop steels with lower overhead costs. Controlled rolled steels, which do not require reheating as normalized steels do, appeared to be the solution to the problem; but the oil shortage of the 1970's did not last very long. As energy became less expensive, the emphasis shifted away from the new generation of HSLA steels back to the conventionally manufactured steels. Undoubtedly many steel manufacturers found it much less expensive to operate their current equipment with a larger overhead, than to lay out vast sums of money for new equipment. It is the opinion of some metallurgists that when energy costs increase again, HSLA steels will once again make large gains into the American steel market place.

Domestic plate steel shipments are summarized in Tables 7 and 8. For long term planning it better to use Table 7 because it reflects the data as averaged over a number of years, and it is not as volatile as Table 8, which lists the data in intervals of one year.

Years		1960-62	1963-67	1968-72	1973-78	1978-82
Carbon	Tons	6,025	7,947	7,195	7,472	5,834
	% Change		+31.9	-9.5	+3.8	-21.9
Full Alloy	Tons	227	299	310	367	339
	% Change		+31.7	+3.6	+18.4	-7.6
HSLA	Tons	343	712	890	1,242	1,307
	% Change		+108	+25.0	+39.6	+5.2
Total	Tons	6,595	8,958	8,395	9,081	7,480
	% Change		+35.8	-6.3	+8.2	-17.6

Table 7. Average domestic plate steel shipments (thousands of tons) by grade since 1960 [6].

Years		1978	1979	1980	1981	1982
Carbon	Tons	6,721	6,971	6,387	5,950	3,141
	% Change		+3.7	-8.4	-6.8	-47.2
Full Alloy	Tons	357	357	348	364	267
	% Change		0	-2.5	+4.6	-26.6
HSLA	Tons	1,545	1,737	1,366	1,145	744
	% Change		+24.4	+12.4	-21.4	-32.4
Total	Tons	8,623	9,065	8,101	7,459	4,152
	% Change		+5.1	-10.6	-7.9	-44.3

Table 8. Yearly domestic plate steel shipments (thousands of tons) by grade since 1978 [6].

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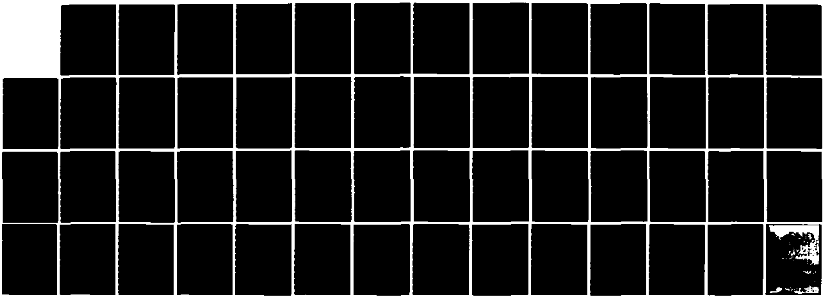

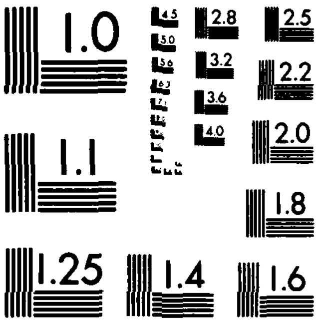

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

HIGH STRENGTH LOW ALLOY STEELS COME OF AGE

With a statistical background developed that traces the trends of HSLA steels, and compares their performance against both plain carbon and full alloy steels, it would be useful to investigate their surge in popularity.

The impacts of the most recent oil shortages reverberated throughout the American automobile manufacturing industry. Detroit, caught unaware and unprepared for the sudden demand for fuel efficient vehicles, did all it could to squeeze extra mileage from its products. One of the quickest and easiest methods of increasing an automobile's fuel efficiency is to make it lighter; as a result American designers began to substitute plastics, fiber composite products, and steels with higher strength-to-weight ratios for the traditional automobile raw materials. In the four years from 1975 to 1978 the average weight of HSLA steel in an American made automobile increased from 100 pounds to 133 pounds. The figure for 1978 represents only three percent of the total vehicle weight, but projections for 1985 estimate that this amount will rise to ten percent [7], [8].

This is not to imply that HSLA steels are not being used very much. Applications for HSLA steels are being developed daily. The exploration and retrieval of natural resources from the arctic regions by the offshore industries has focused much attention upon these new steels because they generally have high strength and toughness levels. The U.S. Navy is currently conducting an extensive and thorough certification program for HSLA steels so they may be used in their shipbuilding program.

As the Navy views the problem, the shipbuilding materials and techniques presently used have many problems which it hopes can be alleviated. Amongst those problems are: those which arise due to the fact that welding is a high cost and labor intensive process, the fact that there presently is an insufficient pool of skilled welders (with no immediate change anticipated), those high strength materials developed in the past require greater erection skills and tolerate fewer defects, and HY-80 and HY-100 steels which are used extensively throughout the Navy are costly to obtain and fabricate.

Near term goals of the Navy are the certification of an 80 KSI yield strength steel, with a 100 KSI yield strength steel as an ultimate goal. For the 80 KSI applications, the HSLA steels would be used to replace HY-80, High Tensile Strength (HTS), and occasionally Mild (MS) steels. These steels are typically used for structural members and crack arresters. Furthermore, it has been proposed that the current usage of HY-100 in aircraft carriers could be reduced by the substitution of a 100 KSI high strength low alloy steel [41].

Current specifications for the erection of HY-80 and HY-100 require the usage of preheat before the welding of these steels. Based upon the assumption that the amount of preheat used can be either reduced or totally removed, the Navy projects a savings on the order of 20-40 cents per pound of steel by the substituting HSLA steels for HY-80 and HY-100.

Combined with a savings of 20-50 cents per pound, for the acquisition of the base metal, the net cost differential between HSLA steels and HY-80 and HY-100 is between 40 and 90 cents per pound. This equates to a savings of 5 to 15 percent based upon an estimating rule of thumb of 6-7 dollars per pound for HY-80 and HY-100 [41].

For a guided missile cruiser (CG-47) where 707 (long) tons of HY-80 steel is called for, in thicknesses up to 3/4 of an inch, the Navy has calculated that there exists a potential savings of between $283,000 and $636,000 per ship if half of the HY-80 was replaced. For an aircraft carrier, where 23,000 tons of HY-80 and HY-100 are used in thicknesses no larger than 4.5 inches, if half of the HY-80 and HY-100 was replaced, a possible savings of $9.2 to $20.7 million per ship could be realized [41].

When integrated into the entire Navy shipbuilding program, if HSLA steels were to replace only half of the HY-80 and HY-100 presently called for, a savings of as much as $500 million dollars per decade through the end of this century could be achieved. It must be recalled that HSLA steels can also be used to replace HTS and MS steels, which would add to the savings per ship [41].

The CG-54 is an example where HTS steel will ultimately be replaced by an HSLA steel. Specifications for the CG-47, which called for the usage of HTS steel, were modified by a partial substitution of HY-80. Later the HY-80 was replaced by an ASTM A-710 type HSLA steel, resulting in a projected weight savings of 200 tons for the CG-54. [23].

An examination of the potential weight reduction which could be obtained if an 80 KSI HSLA steel was substituted for 55 KSI HTS was made by the Navy. Based upon a replacement of all structural HTS steel, it was discovered that failure of the resulting thinner sections would not be a problem, and as a result, a net HTS weight reduction of 10 to 30 percent could be obtained. This would translate into 70 to 210 tons per fast attack submarine, 270 to 810 tons per guided missile cruiser, or 220 to 660 tons per destroyer [41].

The total savings which could be realized by the maximum application of HSLA steels is best demonstrated by Tables 9 and 10 where a single DDG-51 class vessel could benefit from a net weight savings of 77.5 tons, and dollar savings of $933,000.

One of the problems associated with HSLA steels that had to be solved was the fact that it is difficult to manufacture formed pieces such as structural shapes. Using the technique of high frequency welding, it is possible to make light weight structural shapes using continuous coils of strip steel (See Figure 22). When welding HSLA steels for the manufacture of structural shapes, a 400 Hz power supply is used, with welding rates up to 55 fpm (280 mm/s) when welding flanges and webs with thicknesses of 0.255 inches (6.5 mm). As the flange and web thicknesses decrease, it is possible to attain welding rates of 150 fpm (760 mm/s) [36].

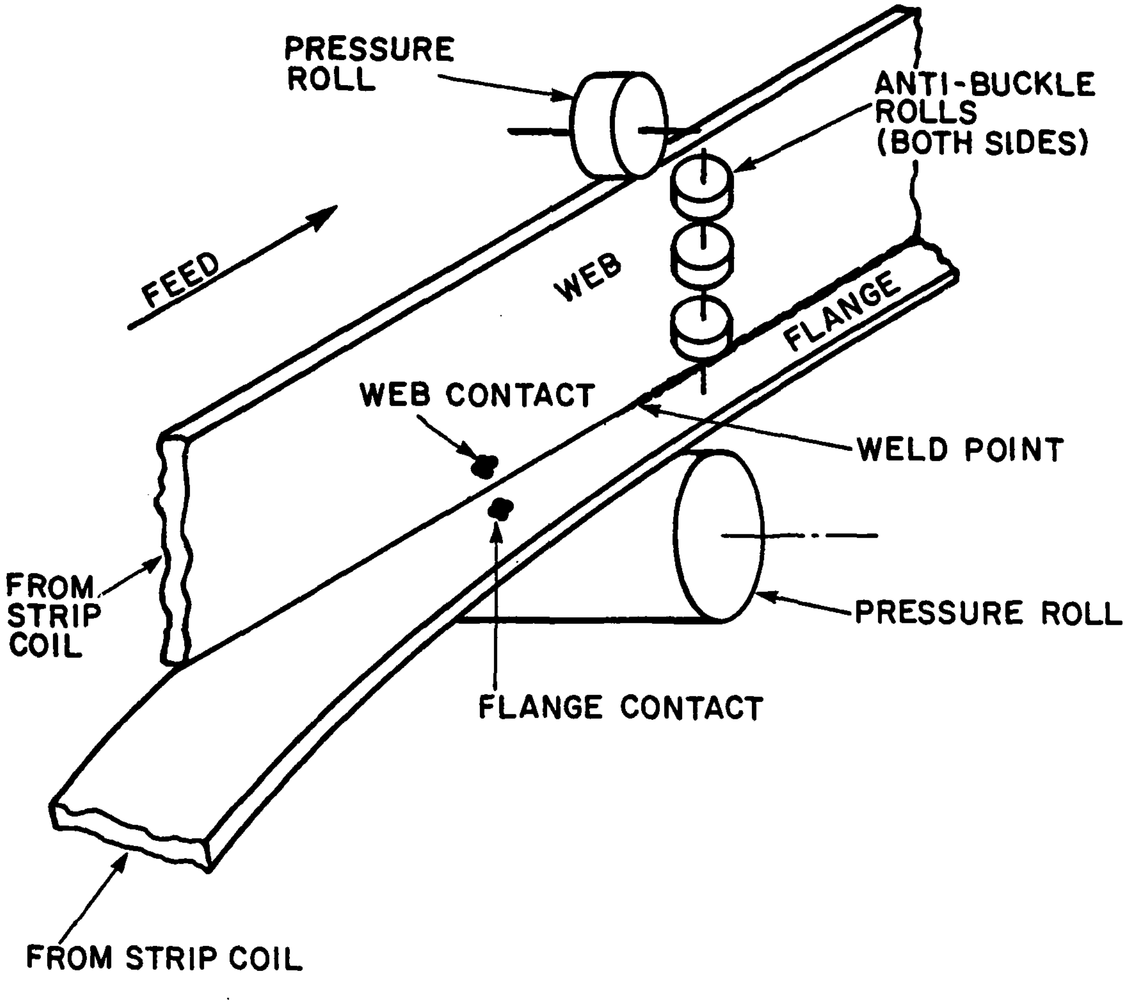

Figure 22. Arrangement for the high frequency welding of a structural "T" beam [40]

SWBS	Item	Current Weight Estimate	HSLA Weight Estimate	Weight Savings
111	Shell, Crack Arrest Plating	64.7 LT (HY-80)	64.7 LT (HSLA)	None
136	01 Level Plating	151.4 LT (HY-80)	154.4 LT (HSLA)	None
117, 131 136, 141 142, 149	Web Frames, Hull & Hull Deck Webs	175.6 LT (HTS)	148.5 LT (HSLA)	27.1 LT
151-156	Superstructure Web Frames, Steel Deckhouse Only	240.0 LT (HTS & MS)	225.6 LT (HSLA, MS & HTS)	14.4 LT
120	Bulkheads	371.6 LT (HTS)	335.6 LT (HSLA)	36.0 LT
Total Estimated Savings Per Ship --------------------				77.5 LT

Table 9. Impact on DDG-51 weight assuming maximum application of HSLA steels [41].

SWBS	Item	Estimated Material Savings	Estimated Fabrication Savings
111	Shell, Crack Arrest Plating	$29 K	$224 K
136	01 Level Plating	$68 K	$571 K
117, 131 136, 141 142, 149	Web Frames, Hull & Hull Deck Webs	None	None
151-156	Superstructure Web Frames, Steel Deckhouse Only	$5.6 K	None
120	Bulkheads	$15.3 K	None
Savings Per Ship		$118 K	$815 K
Total Savings Per Ship --------------------------			$933 K

Table 10. Impact on DDG-51 acquisition cost per ship assuming maximum application of HSLA steels [41].

It is apparent that a considerable savings could be obtained by the replacement of the presently manufactured high strength steels with the new generations of HSLA steels. As the applications for HSLA steels increase, there will be further benefits obtained by their consumers, this is because as HSLA steels become more readily available, they will be sold at increasingly competitive prices.

VI. CONCLUSIONS

Exclusive of the automobile industry, which uses HSLA fasteners and sheet steel, steel plates and thick sections are primarily used in the construction, shipbuilding, and railroad industries. Presently many designers of buildings and bridges are either not aware of the favorable properties of HSLA steels, or they are reluctant to switch from the products they currently use. Although there is an apparently growing Navy interest in HSLA steels, most commercial shipbuilders have little cause to switch from traditional mild steel products. This is because commercial ships, although subjected to severe loads, are rarely designed to meet the demanding conditions that combatant vessels must anticipate. As noted several times previously, there is an interested market for HSLA steels in the offshore industries. The manufacturers of railroad cars, and the "off road" construction industries have found that HSLA steels not only have high strength levels and can be formed easily, but they have the additional property of good "wearability".

The reluctance to use HSLA steels in traditional mild steel applications is best understood by looking at Table 11. When comparing a controlled rolled high strength low alloy steel (HSLA(a)) steel to mild steel for a proposed project, if the fabrication costs of the HSLA steel were to exceed more than 26.1 percent of the combined material and fabrication costs, then the mild steel would would be better suited for the project. For most applications, fabrication costs are a significant portion of the total product expense.

			Relative to Mild Steel		
Steel	Minimum Yield Strength (KSI)	Cost ($/lb)	Section for Equiv. Load Carrying Capacity	Material Cost for Equiv. Carrying	Fabr./ Welding Costs
Mild	32	0.30	1.0	1.0	1.0
HTS	51	0.35	0.63	0.73	2.50
HSLA(a)	80	0.35	0.40	0.47	2.50
HSLA(b)	80	0.60	0.40	0.80	2.50
HY-80	80	0.80	0.40	1.07	6.00
HY-100	100	0.90	0.32	0.96	6.00

Mild steel is ABS grade C
HSLA(a) is a C-Mn controlled rolled steel
HSLA(b) is a quench and tempered alloy steel

Table 11. Comparison of various steels to mild steel [41].

There are also many unanswered questions which need to be investigated. Questions such as, "What happens to the micro-structure near a welded joint of a controlled rolled steel?" This is an important question because the parent metal, which received its properties through the application of precise rolling processes at specific temperatures, has now been allowed to melt and recrystalize freely. Given time and the resources, these and many other areas will be researched, but not without the dedicated efforts of many men and women.

The investigations into new HSLA steels, as accomplished by works such as this, have demonstrated that it is both technologically and practically feasible to manufacture high quality steels with a superior resistance to weld cracking than has previously been attainable. As calculated by the U.S. Navy, HSLA steels have the potential for significant savings when compared to traditional structural steels. This savings is manifested in the decreased preheating requirements and the lower acquisition costs of HSLA steels.

This is not to imply that HSLA steels will be the only steel available in a few years. There are many applications where the costs of HSLA steels are not justified by their high strengths. As an example, for a given application both a proposed mild and HSLA steel exhibit a corrosion rate of 20 mils per year. The HSLA steel design can tolerate a scantling size of 0.2188 (7/32) inches, while the mild steel design requires a minimum thickness of 0.5469 inches. Steel plates when ordered in standard grades require the mild steel be ordered in a thickness of 0.5625 inches. After corroding for two years, the HSLA steel retains only 82 percent of its original load carrying capacity, while the mild steel could still carry 93 percent of its original load. While this example is overly simplified, it does demonstrate that there are occasions where HSLA steels will not be warranted.

It is this author's opinion that HSLA steels will continue to show market growth, both here in the United States, and abroad. As HSLA steels are used more often, their true abilities will be better known, and there will no longer exist such varied opinions as to how well they can be formed. Looking toward the future, it must be realized that in the next century mankind will undergo one of the largest building programs ever imagined, in outer space. High strength low alloy steels, with their presently known potentials, should play a major role in that building program.

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APPENDIX A

Massachusetts Institute of Technology
Department of Ocean Engineering
Cambridge, Mass. 02139
Room 5-308

17 October, 1983

Steel Manufacturing Corporation
101 Main Street
Anywhere, OH 44444

Dear Sirs:

I am currently studying in the Ocean Engineering Department at Massachusetts Institute of Technology. As a part of my thesis I am doing research on steels fabricated and used in the United States, and how they are welded.

Because you are highly respected in the field of steel production, I would appreciate it if you would kindly send me three copies of any catalogues or brochures describing the high strength steels that your company manufactures.

The steels which I am particularly interested in are the controlled rolled, and quenched and tempered structural steels of all grades; including HY-80 and T-1. It is important to my study that the information sent contain all specifications and mil-specs for the respective steels, as well as the strength levels and commonly available thicknesses.

It would be most helpful if you could also provide the additional information requested on the enclosed questionnaire.

I would like to take this time to thank you in advance for your time and cooperation. If answering the questionnaire will delay your forwarding the catalogues, would you please send them in separate mailings. Your assistance is appreciated.

Sincerely,

Frederick Hillenbrand

Enclosure

The questionnaire sent to steel manufacturers contained the below listed questions.

1. Which welding processes does your firm use, or recommend, and what is the practice of your major consumers. For what welding conditions are these processes used, i.e. joint type, joint thickness?

2. Which cracking tests does your company use, and are you satisfied with the results of these tests?

3. Are you aware of the new cracking tests being developed in Japan and Europe?

YES ______ NO ______

4. Would you be interested in using any of the new tests if you were convinced that they are superior to those that you currently use?

5. If your firm is involved with welding, what methods does it use to prevent and control weld cracking, and under what circumstances.

6. Which carbon equivalent formula does your company use?

Massachusetts Institute of Technology
Department of Ocean Engineering
Cambridge, Mass. 02139
Room 5-308

26 October, 1983

Father and Son Shipyard
1 River Drive
Ocean City, NY 11111

Dear Sirs:

I am currently studying in the Ocean Engineering Department at Massachusetts Institute of Technology. As a part of my thesis I am doing research on steels fabricated and used in the United States, and how they are welded.

The specifications for steel erection established by many classification societies and governmental agencies frequently define a minimum set of standards which must be met; while at other times they establish a guideline to be "considered".

Because you are a highly respected shipbuilder, I would appreciate it if you would kindly answer the short questionnaire that I have enclosed, without divulging any corporate or military secrets. It would be most helpful if you could make specific note of the practices that your company uses.

The steels which I am particularly interested in are the high strength steels of all grades; especially HY-80 and T-1. It is important to my study that the information sent contain all specifications and mil-specs for the respective steels, as well as the strength levels and commonly used thicknesses.

I would like to take this time to thank you in advance for your time and cooperation. Your assistance is appreciated.

Sincerely,

Frederick Hillenbrand

Enclosure

The questionnaire sent to the shipyards contained the below listed questions.

1. Which welding processes does your firm use. For what welding conditions (Base plate strength level and thickness, joint type, etc.) are these processes used?

2. Which weld cracking tests does your company use, and are you satisfied with the results of these tests?

3. Are you aware of the new cracking tests being developed in Japan and Europe?

YES ______ NO ______

4. Would you be interested in using any of the new tests if you were convinced that they are superior to those that you currently use?

5. What methods does your company use to prevent and control weld cracking, and under what circumstances. This might include specific practices, such as permissible atmospheric exposure time for low hydrogen electrodes; choice of procedures used; the uses of pre-, interpass, and postheating.

6. Which carbon equivalent formula does your company use?

APPENDIX B

COMPILATION OF SURVEY RESPONSES

This appendix is devoted to the compilation of the responses to the questionnaires (See Appendix A) mailed to the various American steel manufacturers and shipyards.

STEEL MANUFACTURERS

Very specific answers were received from the steel manufacturers regarding the welding practices that they recommended for their products. In an effort not to lose their individual procedures, each manufacturer's response will be detailed separately. Most of the following information was forwarded in separate publications that were returned with the questionnaires.

MANUFACTURER A

This manufacturer suggests the usage of the Shielded Metal Arc Welding (SMAW), Submerged Arc Welding (SAW), Gas Metal Arc Welding (GMAW) and Flux Cored Arc Welding (FCAW) joining processes, dependent upon the thicknesses involved and the welding position. This manufacturer recommends that sources of hydrogen are to be avoided when welding their steels. In an effort to minimize the introduction of hydrogen during the welding process, they suggest that the welding consumables be heated in ovens or cabinets for at least 24 hours at 200° F prior to use. The preheats recommended for their steel products are detailed in Table B-1. Stress relieving at

1150° F for one hour per inch thickness can be performed on all but two specific steel products. For the two exceptions it is suggested that preheat be applied to all joints when the thicknesses become great or when either a high degree of weld restraint exists, or the ambient shop temperature is below 70° F.

Thickness (in.)	*Steel A1*	*Steel A2*	*Steel A3* Chromium added
Yield (KSI)	up to 60	65 & 70	up to 100
< 3/8	70	70	70
3/8 - 1	100	150	70
1 - 2	150	250	100
> 2	200	300	-
2 - 5	-	-	200

Table B-1. *Manufacturer A*, preheat temperature (°F) for high strength steels.

MANUFACTURER B

Manufacturer B also recommends the use of low hydrogen welding procedures when welding their products. Additionally, they suggest the usage of the SMAW, SAW, GMAW, and FCAW joining processes. This corporation returned information on three different types of high strength steels that they manufacture. For the first type of steel, Steel *B1*, if the user determines that postweld heat treating will be beneficial, *Manufacturer B* explains that for temperatures in excess of 950° F intergranular cracking may occur. This steel producer generally does not recommended any form of postweld heat treatment.

Table B-2 outlines the minimum preheat and interpass temperatures to be used with *Manufacturer B*'s products. This steel producer also limits the maximum welding heat input for steels *B2* and *B3*.

Thickness (in.)	*Steel B1*	*Steel B2* min	max	*Steel B3* min	max	*Steels B2 & B3* Max Heat Input
Yield (KSI)	100	80,90,	100	80 &	100	
< 1/2	50	50	200	60	300	45 KJ/in
1/2 - 1	50	100	300	-	-	55 KJ/in
1/2 - 1 1/8	-	-	-	125	300	55 KJ/in
> 1 1/8	-	-	-	200	300	55 KJ/in
1 - 2	150	150	300	-	-	55 KJ/in
> 2	200	-	-	-	-	55 KJ/in

Table B-2. *Manufacturer B*, maximum for preheat and interpass temperatures (°F) and maximum welding heat input for high strength steels.

MANUFACTURER C

Relative to the other manufacturers, this manufacturer did not forward as much material pertinent to the specifications of its steel products. The data for the single steel type that they sent specifies a yield strength of 50 KSI.

Thickness (in.)	Preheat Temperature	Maximum Heat Input
Yield (KSI)	50	
3/4 - 1	100	55 KJ/in
1 - 1 1/2	100	60 KJ/in
1 1/2 - 2	150	65 KJ/in
2 - 2 1/2	150	75 KJ/in

Table B-3. *Manufacturer C*, maximum for preheat and interpass temperatures (°F) and maximum welding heat input for high strength steels.

This manufacturer recommends the usage of the SMAW, SAW, GMAW and FCAW welding processes. It is suggested that this steel be joined by using low hydrogen electrodes and fluxes.

Table B-3 details the recommended preheat temperatures, and maximum welding heat input. *Manufacturer C* does not address the subject of postweld heat treatment.

MANUFACTURER D

The material that *Manufacturer D* forwarded included the specifications for nine different kinds of high strength steels. The ninth steel is not presented here because this manufacturer does not recommend any form of preheat for this particular steel. Many of these steels have very similar properties, and only differ slightly. Some of the steels manufactured by this company are permitted to be joined using other than low hydrogen processes. This is rather unusual, as all of the other steel manufacturers imply that ideally low hydrogen procedures should always be used.

Thickness (in.)	*Steel D1*		*Steel D2*		*Steel D3*		*Steel D4*		*Steel D5*	
Yield (KSI)	50		60		70 & 80		50		50	
	a	b	a	b	a	b	a	b	a	b
< 3/8	50	50	50	50	50	-	-	-	-	-
3/8 - 5/8	50	100	70	100	-	-	-	-	-	-
< 1/2	-	-	-	-	-	-	-	50	50	50
1/2 - 1	-	-	-	-	-	-	-	100	300	350
< 1	-	-	-	-	-	-	50	-	-	-
1 - 1 1/2	-	-	-	-	-	-	-	200	-	-
1 1/2 - 2	-	-	-	-	-	-	-	250	-	-
1 - 2	-	-	-	-	-	-	100	-	350	350
> 2	-	-	-	-	-	-	200	300	350	350

a - low hydrogen process b - other than low hydrogen process

Table B-4. *Manufacturer D*, preheat temperature (°F) for high strength steels.

This manufacturer does not mention the use of postweld heating, but does suggest that the user seek additional information when welding some grades of their product. Tables B-4 and B-5 summarize *Manufacturer D's* heating recommendations.

Thickness (in.)	*Steel D6*	*Steel D7*	*Steel D8*
Yield (KSI)	50	50	60
< 1/2	50	-	50
1/2 - 1	-	-	100
< 1	-	50	-
1 - 2	-	100	-
> 2	-	200	-

Table B-5. *Manufacturer D*, high strength steel preheat and interpass temperatures (°F).

The second question asked of the steel manufacturers inquired about the cracking tests that they used. Only three companies responded to this question.

The Charpy V-notch test is used extensively by all of the respondent steel manufacturers and is followed in frequency by the Drop Weight Tear test. When the Charpy V-notch test is used by a steel manufacturer it generally serves as a quality control test, used to monitor the steel as it is fabricated.

Manufacturer A wrote that they use the K_{IC}, The J integral, Crack Opening Displacement, and R curve tests at the research level for fracture investigations. Additionally, the British Petroleum (BP) and National Association of Corrosion Engineers (NACE) tests are conducted for research in the field of hydrogen cracking. The tests that are used by *Manufacturer A* at the research level are not made available for commercial steel orders.

Manufacturer B is familiar with a large number of weld tests at the research level, these tests have previously been tabulated in Chapter III, Table 2.

Manufacturer E also uses the J integral test, as well as the Wells Wide Plate test, but does not apply them outside of the research field because of the costs.

All of the steel manufacturers that replied wrote that they were aware of new cracking tests that are being developed in Japan and Europe.

Manufacturer E exclusively indicated that they would be interested in new cracking tests. However, they did qualify their response by stating that both the economics of the tests involved, and the specification by the customer must precede the usage of any new tests.

Responding to the question inquiring about methods for preventing weld cracking *Manufacturer B* referenced a brochure they had forwarded with their reply. Additionally manufacturer *B* indicated that a report being prepared at the time of response would further detail their recommendations. Upon receipt of the report, this researcher found that it covered most methods presently known for controlling weld cracking: the preparation of the joint for welding, the cleanliness of materials and the removal of any processing residues or grime, the proper handling and storage of welding consumables, and the removal of stresses and stress raisers, to name a few. Because of the report's thoroughness, it was surprising to discover that the particular welding process selected for a task was not included as a method for controlling weld cracking. It will be recalled that in Chapter II, when detailing the affects of hydrogen upon cold cracking, Figure 5 was used to graphically illustrate the impact of the various welding processes upon the level of hydrogen found in a weld.

The advice given by *Manufacturer E* was very general, and recommended the use of preheating the steel to be welded, and to add interpass and postheat as necessary, combined with proper electrode care and selection.

Steel manufacturers do not advocate the usage of any specific carbon equivalent, rather they will manufacture steels to established specifications, such as the ASTM codes, or use the carbon equivalence formula desired by a customer.

SHIPYARDS

The responses from the shipyards tended to be far more interesting and encouraging from this researcher's point of view. The replies from the shipyards were not always in agreement, and unlike the steel manufacturers, the responses were not always well "groomed". These answers also were more reflective of the knowledge of the reporting individual rather than the combined collective thinking of an entire corporation.

The welding process most widely used by the shipyards was Shielded Metal Arc Welding; 16 of 17 respondents use this process. Shielded Metal Arc Welding is very popular because it is easy to work with, it can be used in very confined positions, and it performs well even under adverse conditions. Furthermore, SMAW has the lowest potential for introducing unwanted hydrogen into a weld. Some shipbuilders are phasing out the usage of SMAW, replacing it with continuous wire welding processes. The advantages gained by introducing extremely low levels of hydrogen are not as valuable to most of these shipyards, this is because they work primarily with mild steels that do not require critical hydrogen control. However, these same shipbuilders admit that there are applications where SMAW must be used. Some of those applications include areas that are inaccessible to other welding processes, and critical welds that join special alloys.

Equally popular is the GMAW process. This form of welding is widely used for aluminums and low alloy steel plates. Its prime advantages include: a high production rate, and it can be automated to various degrees. One shipyard finds that GMAW does not require as much of a cleaning effort as the other welding processes.

GMAW can use three different types of metal transfer modes: spray, pulse, and short circuiting. While many of the shipyards do not state which metal transfer methods they use, some specifically mention all three, while others only use the pulse method.

Fourteen of the seventeen shipyards use the SAW and GTAW processes. When "clean", "smooth" welds have to be made, or when the heat input to the joint must be precisely controlled, GTAW is used. Very frequently GTAW is used in the welding of piping systems; several responses to the questionnaire made specific mention of this application.

Submerged Arc Welds are performed in shops or on the main deck only, with the requirement that the workpiece must be flat. An advantage of SAW is that it can be used on very thick sections, and by using multiple wire systems large amounts of filler metal can be laid down rapidly. Depositing a large amount of filler metal in a single pass conserves energy immediately during the welding process, as well as reducing the total number of hours required for baseplate heating. This is because if a weld must be completed using a multipass procedure, interpass heaters may have to be used if the joint is very thick, or the welding procedure for the steel requires it.

Ten of the seventeen shipyards use some form of FCAW. This process is gaining in popularity as additional filler materials are developed. It can be used with or without shielding gases (CO_2 is usually used) with the gasless method generally used outdoors. Some U.S. Navy specifications specifically require the usage of FCAW.

With few exceptions, the surveyed shipyards do not perform weld cracking tests. The normal testing performed by the shipyards is only intended to reveal production welding defects.

The Liquid Dye Penetrant test is used by ten of the seventeen shipyards, while the Magnetic Particle test is being used by only one less shipyard.

Ultrasonic and Radiographic testing is conducted by six of the shipbuilders, while four rely upon visual inspections. The shipyards using visual testing do not rely exclusively on this "test" method.

The Charpy V-notch, Dynamic Tear, and Explosion Bulge tests are used exclusively by one shipyard, while the Drop Weight Tear test is used exclusively by another shipyard.

There was a single instances of the usage of the Cruciform test. The shipyard employing this test rarely performs cracking tests, but uses the Cruciform test exclusively.

Responses from the shipyards surveyed were mixed regarding the knowledge of cracking tests developed recently in Japan and Europe. Those shipyards interested in new tests would be inclined to use them only if: they duplicated production conditions, were economical, were accepted by regulatory agencies, and were both practical and standardized.

The corporations responding to the questionnaire employ various methods to reduce weld cracking. the corporations responding to the questionnaire. The most common practice is the preheating of the workpiece. Limiting the entrained moisture in low hydrogen electrodes and fluxes was also referenced frequently.

Many shipyards limit the exposure time of low hydrogen electrodes, some permit rebaking of the electrodes and fluxes, while other shipyards do not. Five of the shipyards use rod ovens to keep the moisture content in the electrodes down.

One shipyard prefers to use the GMAW joining process for high strength materials because it does not require the usage of a flux, thus removing one possible source of moisture contamination.

The controlling of interpass temperature and postheating is also used as a method for reducing weld cracking by some shipyards. While some shipbuilders use torches for this purpose, rope and strip heaters are preferred by others because they heat more uniformly.

Other methods used to reduce weld cracking are textbook responses. These methods include: the use of detailed welding sequences to reduce built up stresses, the actual welding techniques employed (Examples include controlled wandering, back step, and cascade.), the cleanliness of the joint, the proper electrode selection, altering the cooling rate, the use of peening and other postweld stress relieving methods, the usage of automatic and semiautomatic welders when possible, and "extensive" filler metal evaluation.

Appendix C details the carbon equivalence formulas returned by the questionnaires.

APPENDIX C

CARBON EQUIVALENCE FORMULAS

As a result of the questionnaires distributed (See Appendix A), many different carbon equivalencies were discovered to be in use at American shipyards. Those carbon equivalencies, along with three other currently popular equations, are included in this appendix.

Of the survey participants, the most commonly used carbon equivalence formula was found to be that recommended by the American Welding Society (AWS) [39]:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{20} + \frac{\%Cr}{10} + \frac{\%Cu}{40} - \frac{\%Mo}{50} - \frac{\%V}{10}$$

The next two equations were equally popular. The first is recommended by the International Institute of Welding (IIW) [30],

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15}$$

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Mo}{4} + \frac{\%Cr}{5} + \frac{\%Ni}{15} + \frac{\%Cu}{15} + \frac{\%P}{3}$$

A single usage of the equation recommended by Stout *et al.* was reported [32]:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{20} + \frac{\%Cr + \%Mo}{20} + \frac{\%Cu}{40}$$

Kobe Steel, Ltd., the manufacturers of the high strength low alloy steel being tested by this research, use the formula that the Welding Engineering Society (WES) of Japan developed and recommend [61].

$$CE = \%C + \frac{\%Si}{24} + \frac{\%Mn}{6} + \frac{\%Ni}{40} + \frac{\%Cr}{5} + \frac{\%Mo}{4} + \frac{\%V}{14}$$

Graville suggests the usage of the following equation for the study of high strength low alloy steels [24]:

$$CE = \%C + \frac{\%Mn}{16} - \frac{\%Ni}{50} + \frac{\%Cr}{23} + \frac{\%Mo}{7} + \frac{\%Nb}{8} + \frac{\%V}{9}$$

All of the preceding equations do not take into account that the amount of carbon used in a steel alters the affects of the alloying elements. Furthermore, the equations recommended by the IIW and WES are thought to be more appropriate for usage when the steel contains more than 0.16% carbon. Based upon this fact, an equation that takes the amount of carbon into account was proposed by Yurioka [61],

$$CE = \%C + A\{\frac{\%Si}{24} + \frac{\%Mn}{6} + \frac{\%Cu + \%Ni}{15} + \frac{\%Cr + \%Mo + \%Nb + \%V}{5} + 5B\}$$

where $A = 0.75 + 0.25 \tanh(20\{C - 0.12\})$.

While carbon equivalence formulas can be useful for comparing the expected properties of different steels, there have been some doubts raised regarding the ability of any carbon equivalence formula in the accurate prediction of the microstructure of an alloy [44].

APPENDIX D

EXPERIMENTAL DATA

All of the plates used for the experimentation performed for this work were welded using the Miller Electric Manufacturing Company's Gas Metal Arc Welding system. This system is semiautomatic, requiring the operator only to set the welding conditions, and locate the workpiece in relation to the welding tip. Once ready to weld the workpiece, the only actions required of the operator are the initiation of the weld sequence (flipping two switches to the *on* position), and the termination of the welding process (flipping the same two switches *off*).

By using this welding system, the steels are joined using the welding process that is the least susceptible to the introduction of undesired hydrogen (See Figure 5), and is consistent in its welding "skill". This latter feature is important because a poorly trained welder can unfairly influence the results of the testing program. By removing the welder, there is less chance of human factors impacting upon the results.

THE WELDING SYSTEM

The welding system consists of the following components: a Miller Deltaweld 650 welding power supply, a Miller DVC-DW-1 digital voltage controller, a Miller CS-4 controller, a Miller S-54D digital controlled wire feeder, a Jetline traveling carriage, and a shielding gas system.

Power for the welding process is transformed by the Deltaweld power supply which changes the 230 volt, 3-phase, 60 Hz electricity entering, into a maximum of 650 amperes, with an open voltage of 14 to 44 volts dc. On its front panel the Deltaweld has a voltage control selector, an ammeter, and a voltmeter. The voltage control selector was overridden by the inclusion of the DVC DW-1, which could more accurately monitor and maintain the desired voltage. The voltmeter indicates the dc voltage at the output of the Deltaweld 650. This meter can not accurately measure the weld voltage because it can not make adjustments due to line losses associated with the length of the welding cables. The ammeter will correctly indicate the welding current because it measures the current output of the Deltaweld 650, since the current in a simple electric circuit is constant around the "loop".

The DVC DW-1 remotely controls the output voltage of the Deltaweld 650 power supply, monitoring its effectiveness via a feedback circuit. The DVC DW-1 has a ten turn voltage control potentiometer, which is set by the operator to the nearest tenth of a volt desired for the welding process. A meter displays a digital output that shows: the welding voltage selected by the operator prior to the initiation of the weld cycle, the open circuit voltage once the cycle has been initiated, but before the arc is struck, and the actual load voltage after the arc is struck.

Control of the welding sequence is handled by the CS-4 controller. It is here that the operator sets the type of welding to be accomplished, the pre- and postflow times for the shielding gas, the burnback time, and the run in speed. Welding can be either spot or continuous. For spot welding an additional control adjusts the spot time; for these tests, continuous welding was selected.

The shielding gas should be used both before and after the welding is actually accomplished. The flow of gas before the weld is begun, insures that all contaminating gases are displaced, while the flow of gas after the weld is completed baths the just-solidified weld pool with the shielding atmosphere. The post flow shielding is important because the hot weld metal is extremely susceptible to absorbing contaminants from the atmosphere for the first few tenths of a second after solidifying. Burnback controls the amount of time that weld current is applied to the filler wire after the wire has stopped feeding. The result of increasing this time is that the wire extending from the welding tip is shortened. If the burnback time is increased too far, the welding tip will be ruined as the wire melts back into it. This would also have the effect of adding a high concentration of the same material that the welding tip is made of, into the extreme trailing edge of the weld; in this case that would be copper. The run in speed is the wire feed speed used after the weld cycle is started, but prior to the arc initiation. After the arc is struck, the wire speed returns to that as set on the Miller S-54D digital controlled wire feeder. The dial for the run in speed is calibrated in percent, which indicates a percent of the selected welding wire feed speed.

The Miller S-54D digital controlled wire feeder has the spindle which holds the spool of filler electrode wire and its associated feeding mechanisms, a digital readout to display the wire feed speed in inches per minute, a control switch to alter the wire feed speed, a purge button, an inch switch, and a remote control switch. The installed purge button does not operate correctly, therefore purging of the shielding gas lines was accomplished by disengaging the feed mechanism, and initiating the weld cycle. This has the affect of starting a weld cycle, but since the weld wire feed mechanism is disengaged the filler wire does not descend to the workpiece. Thus the shielding gas flows through the system. The inch switch is used to "inch" the filler wire to the workpiece, without energizing the welding circuit. As long as the inch switch is pressed, the wire will continue to feed.

Gas fittings are also found on the S-54D controller which direct the selected shielding gases to the area around the welding tip and workpiece.

The shielding gas is obtained premixed in 200 cubic foot cylinders at an initial pressure of 1500 psi. A reducing valve and flow meter combination is used to adjust the flow rate of the shielding gas. The demand for the shielding gas is determined by the S-54D controller which is connected to the flow meter by a gas hose.

Control of the carriage is accomplished by the Jetline carriage controller. By adjusting an uncalibrated dial, the welding speed of the carriage is altered. A toggle switch is used to select the carriage speed, either *weld* speed or *travel* speed. The travel speed is used for fast, rough positioning of the welding tip. The carriage is moved by a dc motor driving a spur gear that engages with a flat track. This part of the system is without a feedback control. A final toggle switch on this panel controls the entire welding cycle, it is the "Weld" switch. By flipping this switch to the *on* position, the welding sequence begins, turning it *off* halts the welding process.

Due to the fact that the carriage speed control is uncalibrated, it was necessary to develop a setting versus carriage speed curve so accurate welding speeds could be obtained.

The operator is require to preset all desired controls, as applicable, before beginning to weld. When the welding tip is correctly positioned, including the distance from the workpiece (which will alter the welding current), and the angles, the steel must be aligned so the weld bead is properly placed. The operator then flips the "Weld" switch on the carriage controller to the *on* position, waits until the arc initiates, and then turns the carriage motor on using its appropriate switch (also on the carriage controller). The operator terminates the weld by flipping the "weld" switch to the *off* position, and turning the carriage motor off.

Tables D-1 through D-5 list the settings used and readings obtained when making the test welds of the three types of steels, for the various preheat temperatures.

Date	12 Apr 84	12 Apr 84	12 Apr 84
Type of Material	K-TEN80CF	HY-80	T-1a
Plate Designation	K7	H7	T11
Preheat (° C)	19	19	19
Preheat (° F)	66.2	66.2	66.2
Type of Wire	MGS-80	AX-90	AX-90
Wire Diameter	0.045"	0.045"	0.045"
Transfer Type	Spray	Spray	Spray
Shielding Gas	80% Argon 20% CO_2	98% Argon 2% O_2	98% Argon 2% O_2
Gas Flow Rate	35 cfm	30 cfm	30 cfm
MACHINE SETTINGS			
<u>A. Millermatic CS-4</u>			
Pre-flow Time	1.0 s	1.0 s	1.0 s
Run in	3.0 %	3.0 %	3.0 %
Burnback Time	0.0 s	0.0 s	0.0 s
Post-flow Time	2.0 s	2.0 s	2.0 s
<u>B. DVC DW-1</u>			
Voltage	31.0	24.5	24.5
<u>C. Wire Feed Speed</u>	500 ipm	450 ipm	450 ipm
<u>D. Carriage Control</u>			
Auto or Manual	Manual	Manual	Manual
Weld Speed	9 ipm	7 ipm	7 ipm
(cm/min)	22.86	17.78	17.78
<u>E. Power Supply</u>			
Current	280 amps	230 amps	230 amps
Heat Input	57.9 KJ/in 22.8 KJ/cm	48.3 KJ/in 19.0 KJ/cm	48.3 KJ/in 19.0 KJ/cm

Table D-1. Welding conditions for the three test steels when welded without preheat.

Date	3 Apr 84	10 Apr 84	10 Apr 84
Type of Material	K-TEN80CF	HY-80	T-1a
Plate Designation	K1	H4	T6
Preheat (° C)	50	50	50
Preheat (° F)	122.0	122.0	122.0
Type of Wire	MGS-80	AX-90	AX-90
Wire Diameter	0.045"	0.045"	0.045"
Transfer Type	Spray	Spray	Spray
Shielding Gas	80% Argon 20% CO_2	98% Argon 2% O_2	98% Argon 2% O_2
Gas Flow Rate	35 cfm	30 cfm	30 cfm
MACHINE SETTINGS			
A. Millermatic CS-4			
Pre-flow Time	1.0 s	1.0 s	1.0 s
Run in	3.0 %	3.0 %	3.0 %
Burnback Time	0.0 s	0.0 s	0.0 s
Post-flow Time	2.0 s	2.0 s	2.0 s
B. DVC DW-1			
Voltage	31.0	24.5	24.5
C. Wire Feed Speed	500 ipm	450 ipm	450 ipm
D. Carriage Control			
Auto or Manual	Manual	Manual	Manual
Weld Speed	9 ipm	7 ipm	7 ipm
(cm/min)	22.86	17.78	17.78
E. Power Supply			
Current	300 amps	255 amps	255 amps
Heat Input	62.0 KJ/in 24.4 KJ/cm	53.6 KJ/in 21.1 KJ/cm	53.6 KJ/in 21.1 KJ/cm

Table D-2. Welding conditions for the three test steels when welded with a preheat of 50° C (122.0° F).

Date	18 Apr 84
Type of Material	K-TEN80CF
Plate Designation	K4
Preheat (° C)	50
Preheat (° F)	122.0
Type of Wire	MGS-80
Wire Diameter	0.045"
Transfer Type	Spray
Shielding Gas	80% Argon
	20% CO_2
Gas Flow Rate	30 cfm
MACHINE SETTINGS	
A. Millermatic CS-4	
Pre-flow Time	1.0 s
Run in	3.0 %
Burnback Time	0.0 s
Post-flow Time	2.0 s
B. DVC DW-1	
Voltage	31.0
C. Wire Feed Speed	500 ipm
D. Carriage Control	
Auto or Manual	Manual
Weld Speed	9 ipm
(cm/min)	22.86
E. Power Supply	
Current	280 amps
Heat Input	57.9 KJ/in
	22.8 KJ/cm

Table D-3. Welding conditions for the second HSLA steel when welded with a preheat of 50° C (122.0° F).

Date	3 Apr 84	10 Apr 84	4 Apr 84
Type of Material	K-TEN80CF	HY-80	T-1a
Plate Designation	K2	H5	T7
Preheat (° C)	100	100	100
Preheat (° F)	212.0	212.0	212.0
Type of Wire	MGS-80	AX-90	AX-90
Wire Diameter	0.045"	0.045"	0.045"
Transfer Type	Spray	Spray	Spray
Shielding Gas	80% Argon 20% CO_2	98% Argon 2% O_2	98% Argon 2% O_2
Gas Flow Rate	35 cfm	30 cfm	30 cfm
MACHINE SETTINGS			
<u>A. Millermatic CS-4</u>			
Pre-flow Time	1.0 s	1.0 s	1.0 s
Run in	3.0 %	3.0 %	3.0 %
Burnback Time	0.0 s	0.0 s	0.0 s
Post-flow Time	2.0 s	2.0 s	2.0 s
<u>B. DVC DW-1</u>			
Voltage	31.0	24.5	24.5
<u>C. Wire Feed Speed</u>	500 ipm	450 ipm	450 ipm
<u>D. Carriage Control</u>			
Auto or Manual	Manual	Manual	Manual
Weld Speed	9 ipm	7 ipm	7 ipm
(cm/min)	22.86	17.78	17.78
<u>E. Power Supply</u>			
Current	290 amps	255 amps	240 amps
Heat Input	59.9 KJ/in 23.6 KJ/cm	53.6 KJ/in 21.1 KJ/cm	50.4 KJ/in 19.8 KJ/cm

Table D-4. Welding conditions for the three test steels when welded with a preheat of 100° C (212.0° F).

Date	3 Apr 84	4 Apr 84	4 Apr 84
Type of Material	K-TEN80CF	HY-80	T-1a
Plate Designation	K3	H3	T5
Preheat (° C)	150	150	150
Preheat (° F)	302.0	302.0	302.0
Type of Wire	MGS-80	AX-90	AX-90
Wire Diameter	0.045"	0.045"	0.045"
Transfer Type	Spray	Spray	Spray
Shielding Gas	80% Argon 20% CO_2	98% Argon 2% O_2	98% Argon 2% O_2
Gas Flow Rate	30 cfm	30 cfm	30 cfm
MACHINE SETTINGS			
A. Millermatic CS-4			
Pre-flow Time	1.0 s	1.0 s	1.0 s
Run in	3.0 %	3.0 %	3.0 %
Burnback Time	0.0 s	0.0 s	0.0 s
Post-flow Time	2.0 s	2.0 s	2.0 s
B. DVC DW-1			
Voltage	31.0	24.5	24.5
C. Wire Feed Speed	500 ipm	450 ipm	450 ipm
D. Carriage Control			
Auto or Manual	Manual	Manual	Manual
Weld Speed	9 ipm	7 ipm	7 ipm
(cm/min)	22.86	17.78	17.78
E. Power Supply			
Current	280 amps	240 amps	240 amps
Heat Input	57.9 KJ/in 22.8 KJ/cm	50.4 KJ/in 19.8 KJ/cm	50.4 KJ/in 19.8 KJ/cm

Table D-5. Welding conditions for the three test steels when welded with a preheat of 150° C (302.0° F).

RESULTS

After the test welds had been made, the steel was allowed to cool. After cooling, each Tekken test plate was X-rayed twice to determine whether any flaws existed, and their extent. (Because it is prohibitively expensive to X-ray a single plate, the second Tekken test plate of K-TEN80CF welded at 50° C was not X-rayed. Instead this plate received an in depth weld cracking search using cross sectioning, which was more cost effective.) Some of the T-1a and HY-80 test welds were poorly made, these test plates were discarded, and additional Tekken tests were made to fill in the missing data. The information found in Tables D-1 through D-5 is reflective of this corrective action.

The X-rayed plates were guaranteed to reveal defects as small as 2 percent of the plate thickness; however, the 1 percent indicator was frequently visible. The plates were X-rayed twice in order to ascertain whether any flaws that were picked up on the film, were the result of the respective Tekken test plate, or because of a mark on the film itself. The results of the X-ray examinations are found in Table D-6.

Because X-ray film can not be reproduced and still retain its original information, Figure D-1 is used to illustrate the test weld regions of each Tekken test plate.

After the X-ray examination, all of the plates were tested for surface defects using a dye penetrant. The results of all of the dye penetrant tests were negative. This test was necessary because X-ray examinations will not always

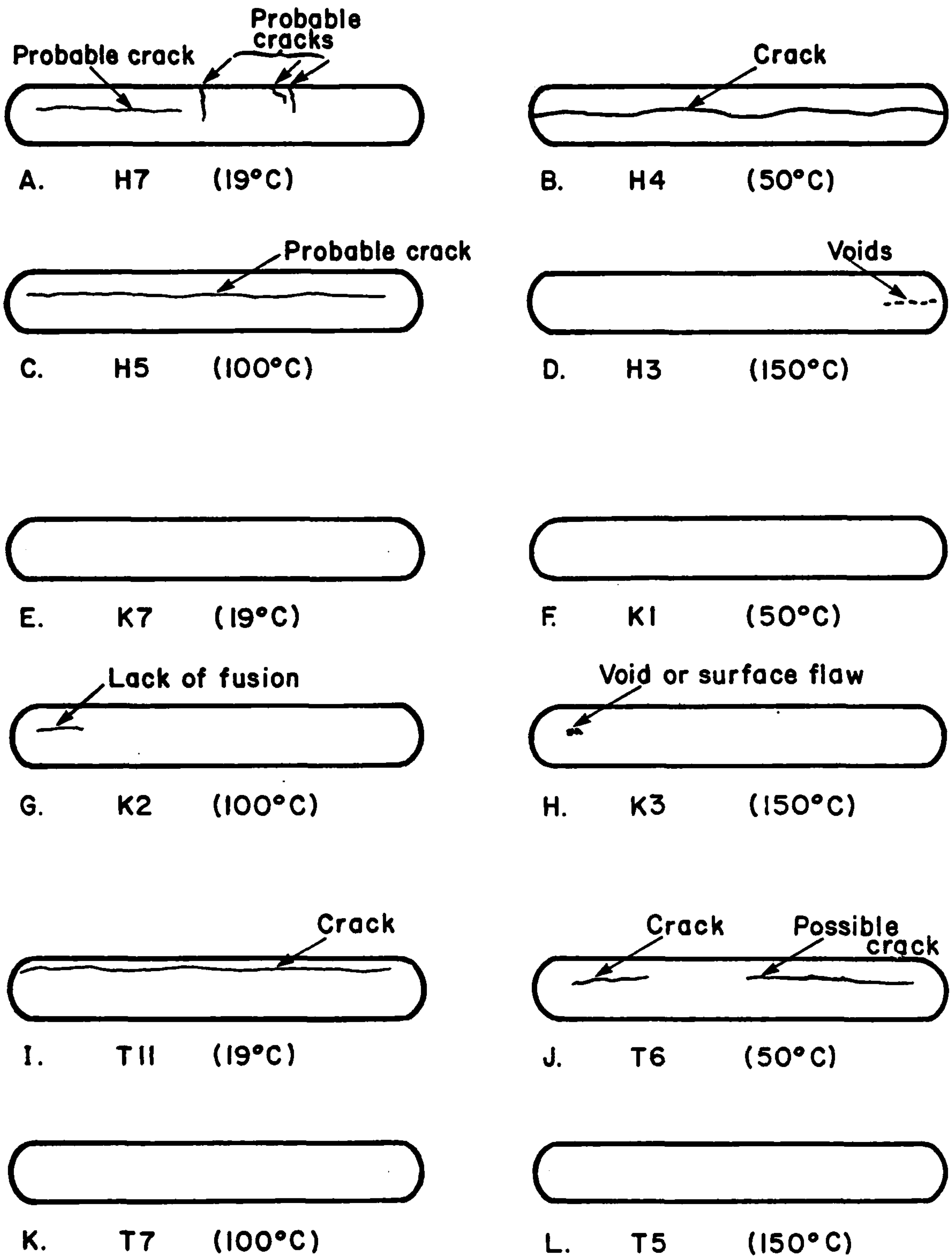

Figure D-1. Results of X-ray examinations of Tekken tests plates in the test weld region reveal surface defects.

Plate Designation	Preheat (° C)	Information Obtained
H7	19	Cracks (?); 2-3 trans. & 1 long.
H4	50	Cracked full length
H5	100	Probably cracked
H3	150	Minor lack of fusion
K7	19	No internal defects
K1	50	No internal defects
K2	100	Minor lack of fusion
K3	150	Possible void or surface flaw
T11	19	Cracked full length
T6	50	Cracked in two regions
T7	100	No internal defects
T5	150	No internal defects

Table D-6. Results of X-ray examination of Tekken tests.

Each test plate was then sectioned either at random, or specifically through a region of cracking or possible cracking as revealed by the X-ray examinations when they existed. After sectioning the plates, a macroscopic examination was quickly performed by an ammonium persulfate etch. The ammonium persulfate will show the different regions of the cross section, including the weld metal, the Heat Affected Zone (HAZ), and base plate. Additionally, the ammonium persulfate made defects more visible to examinations by the naked eye, and those made with a low power microscope. The previous usage of the dye penetrant also aided in this search for defects because it would leach out of any defects that were exposed and were open to the surface of the steel. Those defects not only included cracks, but areas that lacked total fusion as well. The results of the macroscopic examinations are found in Table D-7.

Plate Designation	Preheat (° C)	Information Obtained
H7	19	Possible cracking
H4	50	Cracking of HAZ & weld metal
H5	100	Possible cracking
H3	150	Minor lack of fusion/no penetration
K7	19	No defects noted
K1 (a)	50	Slight crack at root of weld
K1 (b)	50	No defects noted
K1 (c)	50	Cracked at root of weld
K1 (d)	50	Cracked at root of weld
K1 (e)	50	No defects noted
K4 (a)	50	No defects noted
K4 (b)	50	No defects noted
K4 (c)	50	No defects noted
K4 (d)	50	No defects noted
K4 (e)	50	No defects noted
K4	50	No defects noted
K2	100	No defects noted
K3	150	Area with possible defect
T11	19	Root crack into weld metal
T6	50	Cracking of HAZ & weld metal
T7	100	Slight lack of fusion/no penetration
T5	150	Slight lack of fusion/no penetration

Table D-7. Results of macroscopic examination of Tekken tests.

The X-ray examination of test specimen K1, which was welded using a preheat of 50° C, did not identify any cracking. However, the first macroscopic cross section identified a crack. Therefore, a second cut was made to further establish whether or not plate K1 had actually cracked. The second macroscopic cut did not reveal any cracking, implying that the first cut had randomly discovered a defect. The X-ray film for plate K1 was reread, and the crack discovered by the macroscopic cross section could not be found. Since this information did not help to clarify the information regarding

K1, additional sections were made. The additional macroscopic cross sections found plate K1 to be cracked for a significant portion of its length.

Because the information obtained from plate K1 seemed to be contradictory, especially when the information from plate K7, which was welded without preheat, was considered, another plate, K4 was welded with a preheat of 50° C. The second plate, K4, was found to be without cracking even when cross sections were examined microscopically.

Finally, those Tekken cross sections of particular interest, or with a region of questionable quality, were subjected to a microscopic examination. In order to make a microscopic examination, a cross section was cut down to a size so it could be mounted in a one and one-quarter inch *Bakelite* mount. Each specimen was then polished to a 0.05 micron finish, and etched with a one percent nital (nitric acid and methanol) solution. The specimens were then examined using magnifications of up to 1250 times. Table D-8 summarizes the results of the microscopic examinations.

Plate Designation	Preheat (° C)	Information Obtained
H7 (transverse)	19	No cracking noted
H7 (longitudinal)	19	No cracking noted
H5	100	No cracking noted
K4	50	No cracking noted
K1	50	Crack at weld root
K3	150	No cracking noted
T6	50	Cracking of HAZ & weld metal

Table D-8. Results of microscopic examination of Tekken tests.

As a direct result of the microscopic examinations it was found that test plate H7 had neither the transverse or longitudinal cracks which the X-ray examination indicated might exist. Additionally the test plates H5 and K3 were found to be free from defects in the region examined microscopically.

The results of the testing program, which is the product of the examinations detailed above, are found in Chapter IV. For comparison purposes, Table 4 in Chapter IV summarizes the cracking information obtained by each examination method for each plate and preheat.

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